# FINAL REPORT

## High Efficiency – Reduced Emissions Boiler Systems for Steam, Heat, and Processing

## ESTCP Project EW-201016

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The demonstration of a cost effective solution to the problem of improving boiler efficiency and reducing emissions by means of a novel combustion control system and a sensor package was the main objective of this project. United Technologies Research Center and Fireye Inc., worked together to bring the new combustion control and monitoring system from Technology Readiness Level (TRL) 4 to TRL6 and demonstrate its effectiveness in a retrofit of the 30 year old Trane 25 MMBTU boiler at Watervliet Arsenal in NY state. During a one year testing campaign between February 2011 and March 2012, it was demonstrated that the new system would enable fuel savings of about 4% for typical utilization, and a corresponding reduction of CO2 emissions. The investment in the new technology on a similar boiler burning natural gas would pay back in slightly more than 2 years with expected fuel savings of $17,000 yearly. When adopted for all 10-100MMbtu/hr boilers older than ten year across DoD, the demonstrated technology has the potential to save $56 million of fuel costs annually, and avoid the emission of 600,000 tons of CO2.

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## ACRONYMS

AC: Alternating Current

ALC: Automated Logic Corporation (part of Carrier, UTC)

AT: Chemical species transducer (exhaust gas measurement)

BACnet: Building Automation and Control Networks

BMS: Building Management System

CFM: Cubic Feet per Minute

CO: Carbon Monoxide

$CO_2$: Carbon Dioxide

COTS: Commercial of the shelf

DAQ: Data Acquisition System

DB: Database

DoD: Department of Defense

ECIP: Energy Conservation Improvement Program

EPA: Environmental Protection Agency

EH&S: Environment, Health, and Safety

ESCO: Energy Service Company

ESTCP: Environmental Security Technology Certification Program

FDD: Fault Detection and Diagnosis

FMEA: Failure mode and Effect Analysis

FT: Flow Transmitter

FGR: Flue Gas Recirculation

GFCI: Ground Fault Circuit Interrupter

GPM: Gallon per Minute

GUI: Graphical User Interface

HASP: Health and Safety Plan

I/O: Input/Outputs (to a controller or DAQ)

IR: Infra-red

MODBUS: De facto standard communication protocol

NAVFAC: Naval Facilities Engineering Command

NDIR: NonDispersive InfraRed

$NO_x$: Nitrogen oxides ($NO + NO_2$)

PC: Personal Computer

P: Pressure Measurement

PI: Proportional Integral control

PI: Principal Investigator

PM: Particulate Matter

PO: Performance Objective

POC: Point of Contact

PPE: Personal Protective Equipment

RH: Relative Humidity

SoA: State of the Art

TRL: Technology Readiness Level

UESC: Utility Energy Service Contract

UFC: Unified Facility Criteria

URL: Universal Resource Locator

USACE: U. S. Army Corps of Engineers

UTC: United Technologies Corporation

UTRC: United Technologies Research Center

UV: Ultra-violet

VSD: Variable Speed Drive

WebCTRL: Building automation system by ALC (Carrier) used as DAQ

WVA: Watervliet Arsenal

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This report summarizes the activities conducted between August 2010 and March 2012 for the demonstration of advanced control technologies for industrial and commercial boilers. The authors are grateful to the Environment Security Technology Certification Program of the Department of Defense for the financial support and guidance for the duration of the project.

The demonstration would not have been possible without the constant support of the Watervliet Arsenal, who hosted the demonstration. We acknowledge here the amazing help we received from Rich Hoshko, Boiler Plant Manager, and all his staff. Many thanks to Vanessa Duenas, Energy Manager of Watervliet Arsenal, for supporting and enabling the demonstration.

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## EXECUTIVE SUMMARY

The demonstration of a cost effective solution to the problem of improving boiler efficiency and reducing emissions by means of a novel combustion control system and a sensor package was the main objective of the ESTCP funded "High Efficiency – Reduced Emissions Boiler Systems for Steam, Heat, and Processing" project. United Technologies Research Center and Fireye Inc., a UTC Climate, Control & Security Systems company, worked together to bring the new combustion control and monitoring system from Technology Readiness Level (TRL) 4 to TRL6 and demonstrate its effectiveness in a retrofit of the 30 year old Trane 25 MMBtu dual fuel boiler at Watervliet Arsenal in NY state. During a one year testing campaign between February 2011 and March 2012, it was demonstrated that the new system would enable fuel savings of 4% for typical utilization with natural gas, and an equivalent reduction of $CO_2$ emissions. Stated performance objectives (5% fuel costs savings) were not met for the demonstration boiler when fired with natural gas. Nevertheless, the investment in the new technology on a similar boiler burning natural gas would pay back in slightly more than 2 years with expected fuel savings of $17,000 yearly. Although the new system was not tested with No.2 oil, it was demonstrated that 7% fuel savings are achievable with a state of the art efficiency control product on which the new technology is based. When adopted for all 10-100 MMBtu/h oil and natural gas boilers older than ten years across DoD, the demonstrated technology has the potential to save $150 million of fuel costs annually, and avoid the emission of 768,000 tons of $CO_2$.

The demonstrated control solution is intended for retrofit of hot water or steam generation boilers with capacity larger than 10 MMBtu/h. The developed technology includes continuous monitoring of flue gas concentrations of oxygen and carbon monoxide to improve the boiler's fuel to steam efficiency by means of regulation of the burner's inlet fuel valve and air damper. The new boiler efficiency control system incorporates a novel control algorithm, low cost sensors to monitor exhaust composition, and a user friendly tool for visualization of boiler performance. The controller continuously maintains the optimum proportion of fuel and air feeding the burner in order to reduce inefficiencies arising from excess air content while preventing unsafe operation arising from incomplete combustion. This new system is an evolution of commercially available O2 trim solution developed on the Fireye PPC4000 product platform and contrasts with legacy systems with preset mechanical linkage by using electronic driven servomechanisms to set the ratio of fuel to air. The new control algorithm accounts for variation of environmental conditions, e.g., inlet air temperature and humidity, and system degradation.

The demonstration on Watervliet Arsenal's 25 MMBtu/h steam boiler occurred in three phases, aiming at assessing efficiency performance with the legacy mechanical system, the commercially available, state of the art (SoA) electronic O2 trim solution, and the newly demonstrated "CO/O2 trim" solution. In this way, a comparison among technologies and benefits associated with adoption of the proposed solution could be precisely quantified. Stages of the demonstration included (I) the installation of a new sensing and monitoring system and characterization of baseline with legacy control, (II) the installation of a Fireye PPC4000 control system and characterization of SoA control, and (III) software update to CO/O2 trim control and characterization. Accordingly, the boiler was instrumented with metering devices to measure boiler properties such as airside inlet and outlet temperatures, water side flow rate and inlet

temperatures, steam flow, pressure and temperature to allow the precise quantification of boiler fuel to steam efficiency. Data acquisition was performed with Automated Logic Corporation's WebCTRL, enabling reliable collection of performance data but also the demonstration of interconnectivity between a building management system and the Fireye PPC4000 controller. WebCTRL was equipped with a web-based graphical user interface suitable for use by boiler operators.

Boiler performance on all configurations was assessed in terms of combustion efficiency, fuel to steam efficiency, and emission levels. As performance is dependent on the specific operating point of the boiler, the evaluation was performed at different steady state conditions corresponding to levels of steam output and corresponding firing rates. The following was observed for operation with natural gas:

- Combustion efficiency improved with the adoption of O2 trim technology by about 1-2% across the firing range. An additional improvement of 0.5% to 1% was observed by introducing CO/O2 trim at an operation range below 60% of maximum fuel utilization.
- The improvements above had an impact on overall fuel to steam efficiency, with improvements of 2% to 3% with the introduction of O2 trim over baseline, and an additional 0.5% to 1% with CO/O2 trim for operating ranges below 60% of fuel utilization.
- Throughout the demonstration, CO and $NO_x$ levels remained within target boundaries.

Based on standard utilization assumptions and at current fuel prices, it was calculated that, for a 25 MMBtu/h boiler fired by natural gas:

- The adoption of O2 trim would enable yearly savings exceeding 2,400 MMBtu of gas, about 3%, or $13,500 cost savings. The further upgrade to CO/O2 trim technology would enable yearly savings exceeding 3,000 MMBtu of gas, about 4%, or $17,000 cost savings.
- Payback for upgrading to O2 trim technology would be 2 years with an NPV of $77,000 over 10 years. For the CO/O2 trim solution 2.4 years payback and NPV of $88,000 was estimated.
- Every year, 144 tons of $CO_2$ emissions would be avoided with O2 trim, 181.5 with CO/O2 trim technology.

Further:

- Savings and economic indicators would be much more favorable for larger boilers. Estimates for a natural gas fired 100 MMBtu/h boiler showed payback of four months and fuel cost savings in the order of hundreds of thousands of dollars.
- Fuel to steam efficiency improvements of 7-8% were measured across the firing range when No. 2 oil was used as fuel, but demonstration was limited to O2 trim technology. Estimates for operation with oil are of 7% ($140,000) fuel savings and payback of 0.2 years for a 25 MMBtu/h boiler.
- An estimate of potential overall savings across DoD, based on the demonstration results, indicate potential savings of $150 million of fuel costs annually, and avoid the emission of 769,000 tons of $CO_2$.

During the demonstration, the controller performance was observed relative to ease of use, installation and maintainability, and positive feedback relative to its deployment was collected. The new CO/O2 control solution was tested at its prototype stage (TRL6) and further development, testing, and certification is needed for product release (TRL8).

Alternative approaches to improve the efficiency of legacy boilers include replacement of the boiler's burner or heat exchanger elements to enhance combustion efficiency and heat transfer effectiveness. While such modifications can lead to substantial fuel to steam efficiency improvements, they are also expensive. Replacement of the boiler control system with O2 trim or CO/O2 trim is instead the technology enabling immediate savings and shorter payback. Alternative control technologies (e.g. based on optical characterization of flames or on measurements of hydrocarbons rather than CO) have been proposed but have not found yet broad adoption. It is possible however that maturation of those technologies in the future could bring to the market alternative approaches to combustion control optimization.

In summary, it was demonstrated that combustion control technology is a viable solution to achieve substantial fuel savings and reduced carbon footprint, easy to install for boiler retrofit, enabling quick return on investment. In particular, it has been shown how CO/O2 trim technology can lead to substantial energy savings. Adoption across DoD will be facilitated by this study and enable further engagement with key decision makers in installations and energy service companies.

# 1. INTRODUCTION

## 1.1 BACKGROUND

The proposed technology development aimed at demonstrating a cost effective solution to the problem of improving boiler efficiency and reducing emissions by means of novel combustion control systems together with the introduction of a suite of gas sensors. Target boilers for the new technology are hot water or steam generation plants with capacity between 10 and 100 MMBtu/h, fueled by either natural gas or No. 2 oil.

Combustion of fossil fuels is still by far the most utilized technology for generating hot water and steam in industrial and commercial applications. Environmentally cleaner and renewable energy technologies lack the flexibility and availability required for most near term applications. High efficiency, low emission combustion is therefore considered the most viable approach to reduce fuel cost and mitigate undesired environmental effects. In the United States there are approximately 163,000 industrial and commercial boiler systems delivering steam for industrial processes, space heating and hot water. Boilers with capacity larger than 10 MMBtu/h account for 28% of the total, and provide 85% of the overall US boiler capacity. Ninety three percent (93%) of all such systems are more than 10 years old [ORNL 2005] and typically operate at efficiencies between 70 and 80% [Harrold 1999]. Under the pressure of rising fuel costs and increasingly stringent policies limiting the emissions of polluting gases and overall carbon footprint, boiler owners are looking at cost effective ways to renovate legacy systems.

Three possible paths to renovation are currently available: (1) replacement with new boilers (either condensing boilers allowing efficiencies above 90% or non-condensing ones with improved heat exchanger, burner and control system); (2) replacement of the burner for better air/fuel mixing and combustion or (3) adoption of state of the art combustion control systems. While the first and second paths lead to the highest efficiency gains, they are capital investment intensive with payback of multiple years [Durkin 2006], and often require significant infrastructural changes which further add to cost. In the case of condensing units, higher efficiency is gained at the price of reduced fuel flexibility and potential durability issues associated with corrosion. An upgrade of the combustion control system is a more cost effective solution [Eoff 2008] often generating payback in less than one year [Wright 2001] due to lower first cost and significant recurring fuel savings associated with more efficient boiler operation.

Reducing boiler inefficiencies, fuel expenditures and emission output is key towards meeting DoD goals on energy security and environmental impact in line with DoD Instruction 4170.11 [DoD 2005]. This directive includes efficient boilers among the recommended solutions for facility energy conservation. Of the $3.5B per year the DoD spends on facility energy consumption, ~$850M (25%) of it is estimated to be for fuel consumption in boilers larger than 10MMBtu/h, based on an equivalence to the US inventory [EIA 2003]. A 10 MMBtu/h boiler is large enough to provide space heating to buildings ranging from 200,000 to 3300,000 sq ft [Bell 2007], depending on building type and location. The Army owns 214 sites with >10 MMBtu/h oil/gas boilers for a total capacity of almost 34,000 MMBtu/h, more than 90% of which are older than 10 years. The total boiler capacity for DoD can be estimated at 82,000 MMBtu/h by scaling proportionally with total owned building area (data from [FRPC 2006] and [Andrews 2009]). Clearly, the DoD objective to increase energy efficiency and reduce carbon footprint must include solutions targeted to large boilers.

The State of the Art (SoA) approach to upgrading the combustion control systems consists of substituting the mechanical linkage between the air inlet damper and the fuel inlet valve with a digital controller acting on electromechanical positioning servomechanisms. The controller sets the opening of fuel and air inlets at all working conditions (firing range) of the boiler as imposed by the installer during a commissioning phase. In addition to this so-called parallel positioning controller, an *$O_2$ trim* function ensures that the oxygen concentration measured in the exhaust gases is kept at a pre-set low value (generally 4%, depending on the burner installed), thus allowing efficient operation under all boiler working conditions.
While the current technology can ensure efficiencies around 80%, it has the following shortcomings, which prevent reaching the highest possible efficiency gains through combustion control:

- Flue gas $O_2$ concentration cannot be further reduced because of safety concerns associated with incomplete combustion. For this reason, efficiency is not increased further, limiting gains to ~5%.
- The commissioning of the system is performed manually, which can lead to configuration errors and variability leading to suboptimal operation, as well as progressive mistuning.
- Continuous emission monitoring is unavailable, preventing minimum emission operation and real time verification compliance with air permits.
- Calibration for a specific fuel is necessary, so that adopting fuels other than oil and gas is not practical.
- Commercially available $O_2$ sensor stack probes are expensive (~$10K sensor installed cost), thus decreasing the economic attractiveness of the retrofit.

Hence there is a need for a safe, low cost, robust approach that can be easily retrofitted into legacy boiler systems, with continuous optimization of air/fuel controls to attain maximum efficiency while monitoring and controlling operation to meet local emission regulations. Satisfying this need will reduce fuel consumption and carbon footprint in older boiler systems enabling them to be operated at the highest efficiencies possible through tight closed-loop control while maintaining low CO and $NO_x$ emissions.

## 1.2 OBJECTIVE OF THE DEMONSTRATION

The project's objective was to mature boiler controls technology that enables higher efficiency operation of boilers via a simple changeover of the current legacy air-fuel mechanical linkage.
The objective of the demonstration at Watervliet Arsenal was to evaluate and quantify performance of the new boiler control technology relative to baseline and SoA boiler control solutions. Performance in terms of energy savings benefits was characterized relative to the following innovation elements:

1. *CO, $NO_x$, and $O_2$–based boiler feedback control*. By using online feedback based on flue gas concentration measurements in addition to $O_2$, the new technology was expected to enable improved boiler efficiency over SoA while maintaining margin of safety under a broad set of conditions (e.g. varying air humidity, fuel composition, plant variability). <u>Performance of this technology was validated at the demonstration site by collecting boiler operation data during the 2010-2011 and 2011-2012 heating seasons.</u>

2. *Low cost sensors for CO, $NO_x$, and $O_2$ concentrations*. Commercial off the shelf (COTS) sensors packaged to be able to robustly measure target gas species concentration. Robustness of the technology under demonstration includes ability to operate under typical boiler room settings, ability to operate over time within an acceptable accuracy and limited drift, ability to operate for safety critical applications by means of diagnostic functions. Operation of integrated gas sampling and measurement devices was evaluated during the demonstration relative to different types of low cost sensor technologies as compared to laboratory grade ones.
3. *Assisted commissioning*. By utilizing assisted commissioning technology which automates the boiler setting across the operating range, a reduction of commissioning time by 30% is achieved. Evaluation of commissioning times was partially performed during the demonstration, and assisted commissioning algorithm technology was not evaluated due to implementation problems during the execution of this demonstration program. While we still believe that semi-automated procedures would enable more robust and predictable commissioning, it is also true that the introduction of the user interface on PPC4000 enabled significant simplification. In fact, through 2011 Fireye observed that the introduction of the new with simplified access to commissioning procedures has enabled by itself up to 4x time reduction (typically from 8 h to 2 h). Therefore, plans for prototype implementation and future commercialization of assisted commissioning features have been postponed by Fireye as it is expected that it would have only an incremental improvement on commissioning time relative to using the PPC4000 interface.

Additional elements that were validated during the demonstration included ease of use of the new boiler control technology during boiler set up and operation. Such attributes had to be ensured for plant managers and operators to fully benefit from the new technology as intended. To that end a visualization interface was deployed, displaying key performance metrics and operator tunable system parameters allowing boiler operators to visualize boiler operation online.

## 1.3 DRIVERS

Regulations and directives driving the need for demonstrating advanced boiler control technology are listed as follows:

- Energy Policy Act of 2005: Directs federal agencies to purchase Energy Star and FEMP-designated products when procuring energy-consuming items covered by the Energy Star program. Agencies must also incorporate energy-efficient specifications in procurement bids and evaluations. EISA 07 Section 525.
- Energy Independence and Security Act of 2007 (Title IV Subtitle C): requires that U.S. federal agencies improve energy efficiency and reduce greenhouse gas emissions by 30% by 2015 relative to a 2003 baseline. It also requires (sec 433) that new federal buildings must reduce fossil fuel-generated energy consumption, with 2003 as baseline, by 65% in 2015 and 100% by 2030. Provisions require Federal procurement to focus on ENERGY STAR and FEMP-designated products.
- National Energy Conservation Policy Act (42 U.S.C. 8254(a)(1)): mandates the use of practical and effective present value methods for estimating and comparing life cycle costs for Federal buildings, using the sum of all capital and operating expenses associated with the

energy system of the building involved over the expected life of such system or during a period of 40 years, whichever is shorter, and using average fuel costs and a discount rate.

- Emergency Economic Stabilization Act of 2008: contains provisions for incentives relative to replacing equipment with high efficiency technology.
- Executive Order 13423: mandates that new construction, major renovations, and repairs/alterations must comply with Guiding Principles (Optimize Energy Performance: energy efficiency, on-site renewable energy, measurement and verification and benchmarking) and 15% of existing building inventory by end of FY2015 incorporates outlined sustainable practices (sec 2(f)/OAA 09, sec 748).
- Instruction 4170.11: provides procedures for DoD installation energy management and pertains to all phases of administration, planning, programming, budgeting, operations, maintenance, training and material acquisition activities that impact the supply, reliability and consumption of energy at DoD installations. This includes directives for upgrade to low energy solutions for new construction as well as renovation under the Energy Conservation Investment Program (ECIP).

If implemented across DoD, the technology demonstrated in this project would contribute to the increase of energy efficiency towards meeting EISA's stringent energy efficiency requirements and adopting more sustainable practices as instructed by EO 13423. The proposed technology in combination with others aimed at reducing energy demand and making supply more efficient would enable meeting those goals. The application of the CO/O2 trim control technology, if applied to new boilers, would enable energy saving necessary for obtaining Energy Star certification for the whole boiler system. Widespread boiler control updates could be possible by mandating their adoption and incentivizing upgrades via the ECIP program. The adoption of this technology would become even more relevant in the short term, as ramp up of renewable energy heating solutions on a large scale would occur in much longer term. Finally, whenever combustion-based renewable solutions are adopted (biofuels, biomass systems), the technology demonstrated in this project would find direct applicability.

# 2. TECHNOLOGY DESCRIPTION

## 2.1 TECHNOLOGY OVERVIEW

A cost effective solution for controlling and monitoring boiler efficiency and emissions was demonstrated, with expected ability to improve fuel efficiency by at least 5% when used to retrofit DoD boilers with legacy control systems. The expectation was to outperform state of the art commercially available controllers by achieving an incremental 1.8% efficiency gain. The system includes continuous monitoring of flue gas emissions, reducing them (particularly carbon emissions) where possible by regulating the burner's inlet fuel valve and air damper. A user friendly visualization environment was developed to monitor fuel cost savings, carbon footprint reduction and estimated emission levels. Advanced commissioning procedures were initially proposed to reduce installation and recalibration times, the occurrence of mistuning, and the need for frequent recalibration. However, those were not implemented in the final demonstration. The technology was demonstrated on a legacy, single burner 25 MMBtu/h boiler located at the Watervliet Arsenal central steam plant. The existing legacy combustion efficiency controller, based on mechanical linkage technology was replaced with Fireye's SoA solution with $O_2$ trim. This controller was then updated with the novel control logic making use of additional measurements of flue gas CO and $NO_x$ concentrations. COTS exhaust sensors was utilized making the proposed system cost effective compared with commercially available systems.

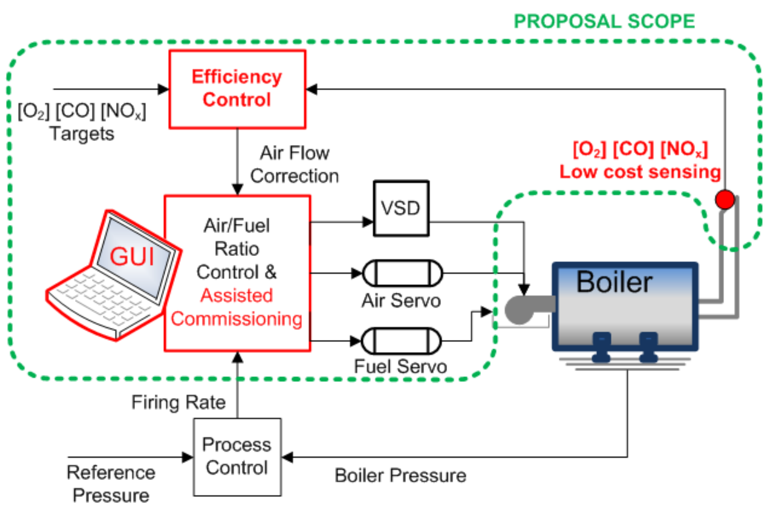



Figure 1 – Schematic of the technology demonstrated as originally depicted in the demonstration plan. All technology elements were implemented during the program.

Boiler fuel efficiency can be controlled by setting the correct proportion of fuel and air feeding the burner, and depends on the unburned fuel, the inlet and outlet temperature of the gases, and the oxygen content of the exhaust [BS 1987]. Boiler efficiency decreases as the air/fuel ratio increases; this change is accompanied by increase in the exhaust oxygen concentration. In contrast, very low air/fuel ratios results in incomplete combustion and potentially unsafe conditions manifested by a sharp increase in exhaust CO concentration. In legacy systems the fuel-air ratio is maintained by a mechanical linkage, while state of the art solutions are based on parallel positioning, $O_2$ trim technology. The unavailability of information on flue gas

composition and relatively imprecise positioning of air and fuel opening require linkage systems to be set to operate often with 8%-10% excess $O_2$ [DoE 2006][WSU 2003] to guarantee an adequate safety margin [Eoff 2008]. Part load operation, variable environmental conditions, system drift, and linkage hysteresis over time cause performance degradation towards either more inefficient operation or potentially unsafe conditions (Figure 2). For this reason, legacy boiler efficiencies often degrade over time, resulting in estimated efficiencies of about 75%.

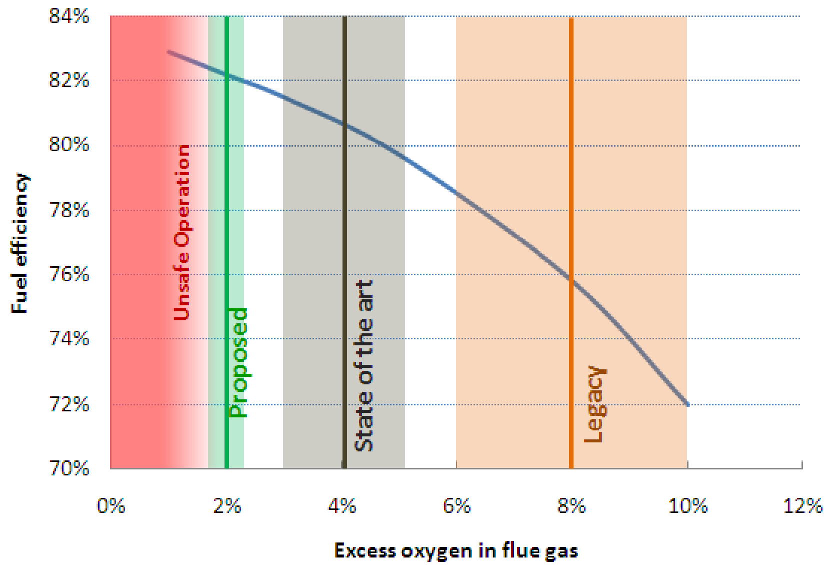



Figure 2 – Efficiency gain enabled by reduction of excess air and variability [Harrold 1999]. Evolution from 'legacy' to 'state-of-the-art' to proposed new technology.

In SoA solutions, improved positioning and $O_2$ concentration measurement enable the reduction of safety margins to a typical value of 4% and reduction of variability due to environmental factors and degradation, allowing efficiencies around 80%. The boiler and burner characteristics affect the efficiency curve and the region of safe operation and consequently the achievable efficiency. As SoA systems are based on microcontroller technology, the setting of the desired air & fuel servomechanism positions across the boiler's operating range can be performed manually during commissioning by operating a menu-based digital interface. It is imperative that menu-assisted procedures are intuitive enough to enable fast and precise setting.

The demonstration technology consists of the following innovation elements:

1. **Control function update**: A novel control algorithm to ensure safe operation while permitting operation to as lower than 2% excess oxygen concentration through feedback on CO emissions in addition to oxygen.
2. **Sensing devices**: In-situ low cost gas sensors of $O_2$, CO, and $NO_x$ for continuous emission monitoring of the exhaust composition and feedback to the combustion controller.
3. **Easy commissioning features**: Simplified manual commissioning procedures enabled by the new PPC4000 menu-based interface for quick setting of the air/fuel ratio across the boiler operating range allowing reduction of boiler commissioning time and better precision relative to fully manual procedures. This approach has been preferred to a semi-automated one which was originally proposed (see Section 1.2).

4. **Graphical User Interface:** A monitoring and data logging device providing real time visualization of boiler performance metrics to the operator to enable continuous monitoring of boiler performance.

Advancement to date of the demonstration technology can be summarized as follows:

2006: Fireye and UTRC developed SoA algorithm to achieve higher boiler efficiencies via $O_2$ trim

2007: Development and demonstration of assisted commissioning algorithm on Fireye experimental boiler

2008: Open loop demonstration of feasibility of efficient boiler operation with monitoring of CO concentration on Fireye experimental boiler

2009: Low cost multi-sensor system prototyped at Fireye for application on large boiler and power plant systems.

Jun 2010: 4 different algorithms of $CO/O_2$ trim controls conceived at UTRC and demonstrated on Fireye's experimental boiler.

Sep 2010: Fireye PPC 4000 parallel positioning boiler control system is released. The same hardware platform and part of the software components will be utilized as part of the demonstration technology.

Nov 2010: A multi-sensor box prototype is designed and built to enable stack exhaust gas sampling and continuous monitoring of $O_2$, $NO_x$, and CO.

Mar 2011: The $CO/O_2$ trim algorithm is finalized, including new features such as fuel "micropulsing" to anticipate the onset of CO spikes and therefore increase control operation safety. The control is implemented in a rapid prototyping environment and tested at Fireye's experimental boiler facility.

Apr 2011: Fireye PPC4000 with SoA $O_2$ trim control product is released. The system includes a user interface with simple key-in configuration and intuitive menus. Users praise Fireye for its simplicity and claim that commissioning time can be reduced by 1/3 compared to competing and earlier generation systems.

Jun 2011: An alternative CO sensor system prototype is designed and built. This prototype utilizes non dispersive infrared technology (as opposed to electrochemical cell) potentially resulting in increased accuracy and reduced maintenance.

Nov 2011: The $CO/O_2$ trim control feature is implemented on PPC4000 and tested at Fireye's boiler experimental facility. Closed loop control is ensured by a CO and $O_2$ monitoring box developed by Fireye which featured dual CO electrochemical cell sensing for improved redundancy.

Jan 2011: The new control system is installed at Watervliet Arsenal. After onsite testing for calibration and algorithm adjustments, performance characterization of the controller begins.

The demonstration of the technology enabled the team to validate that the system is applicable for retrofitting of >10 years old gas and oil non-packaged boilers (10-100 MMBtu/h capacity) with linkage-based control systems. The technology can be applied to any type of commercial boiler (firetube as well as water wall tube) and burner. Scaling within the applicable range is ensured by the availability of servomechanisms with three torque levels. Utilization on boilers with air blowers controlled by a variable speed drive is also possible by exploiting PPC4000 VSD capability. The system can also be installed on new non-packaged, noncondensing boilers.

## 2.2 TECHNOLOGY DEVELOPMENT

As anticipated in Section 2.1, a new efficiency control algorithm was introduced to replace the existing $O_2$ trim control on the existing Fireye PPC4000 platform. The efficiency algorithm communicates with air/fuel positioning controls to dispatch optimal settings for the air and fuel servo-mechanisms actuating the air damper and natural gas supply valve. Information on the concentrations of $O_2$ and CO is provided to the controller by a continuous emissions measurement unit which leverages low cost gas sensor technology utilized in the automotive industry. Two additional gas monitoring devices (ultimately not used for control purposes) were installed to provide additional information on $NO_x$ emissions, gas emissions redundancy, as well as evaluation of alternative CO sensing technologies (specifically NDIR technology as opposed to electrochemical cells). The system also includes a Graphical User Interface based on Automated Logic Corporation's WebCtrl, who communicates via BACnet to an ALC data acquisition module connected via MODBUS to the PPC4000 controller and the additional sensor boxes. The GUI is able to report all operating information about the boiler, including energy performance and continuous monitoring of polluting emissions to the boiler operator. The solution enabled quick turnaround from concept to demonstration prototype, as existing hardware components were fully leveraged to implement the new control functionality. A block diagram of the overall system is illustrated in Figure 3.

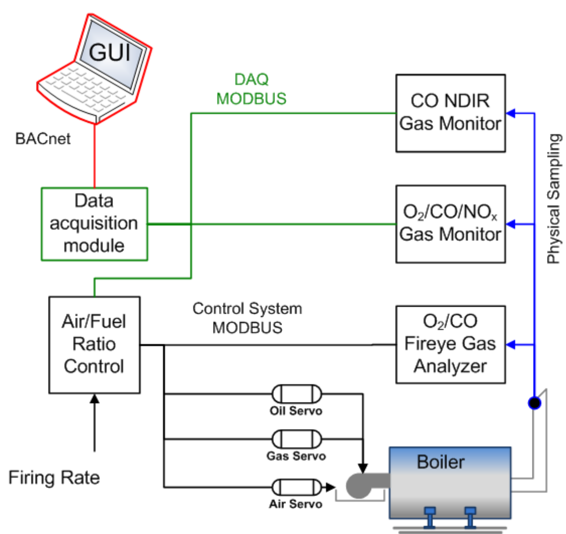



Figure 3 – Block diagram of the system

### 2.2.1 The Controller

The existing PPC4000 control platform was used to implement the new $CO/O_2$ trim algorithm. This approach maintained and leveraged the existing features that guarantee boiler safe operation, including the flame safeguard system, interlocks, and alarm management. In addition, the algorithm was engineered so that the system would fall back to $O_2$ trim operation in case of failure of the CO measurement sensor of the control system. The algorithm control scheme is illustrated in Figure 4. A positioning control selects the positions of air and fuel servos based on information on the boiler desired firing rate. The $O_2$ trim control corrects the air position by ensuring that the $O_2$ concentration in the stack tracks a desired reference value, also dependent on the firing rate and set at boiler commissioning. The proposed control algorithm adds to the standard $O_2$ trim a correction module which uses the CO concentration measurement to prevent unsafe fuel rich conditions from being reached. In this way, the boiler can be operated as close as possible to the point of maximum efficiency. As the correction module is separate from the other control function modules, it can be disabled without interrupting the operation of the standard O2 trim algorithm.

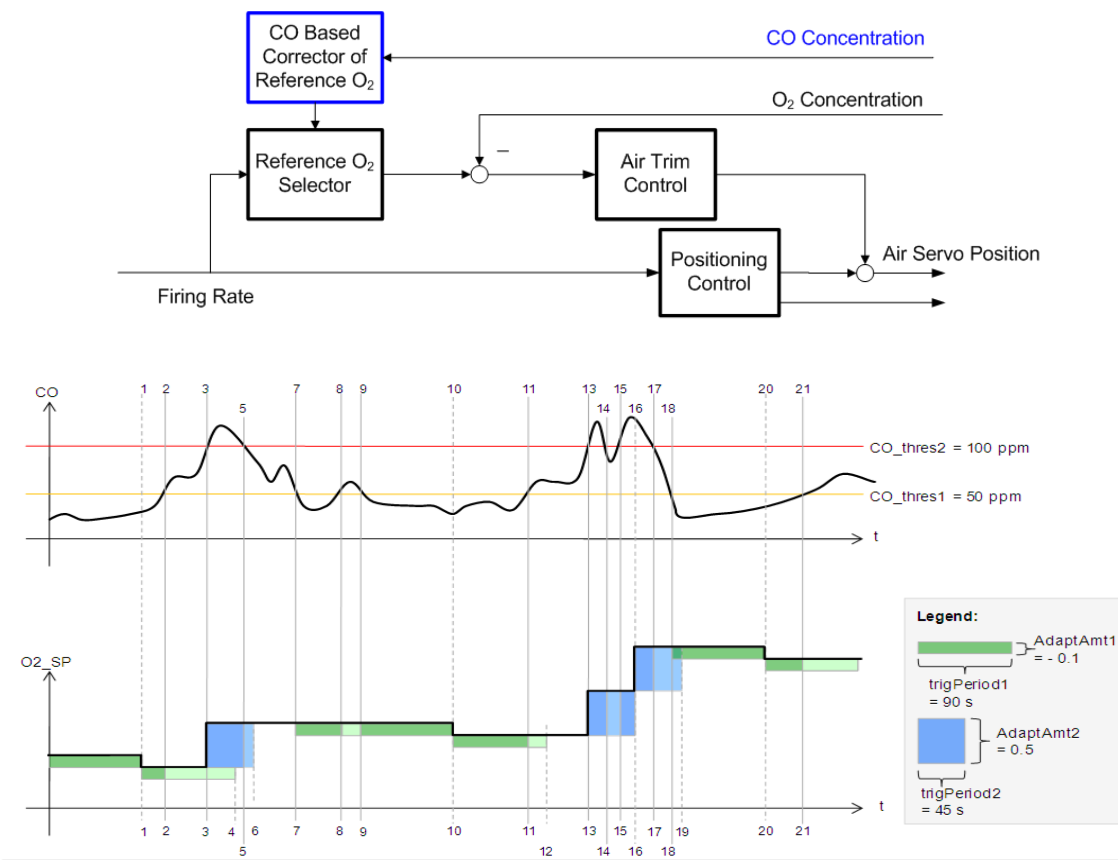



Figure 4 – Block diagram of the proposed algorithm and its functioning. The CO concentration measurement is used to correct the O2 trim algorithm.

The controller is operating as follows:

- When CO concentrations are below a CO_thres1 level (tunable), the algorithm periodically

reduces the target $O_2$ concentration, thereby increasing combustion efficiency.

- If CO concentrations exceed CO_thres1 but are below CO_thres2, the algorithm stops any adjustment of the $O_2$ concentration target.
- If finally CO concentrations exceed CO_thres2, the algorithm will increase the $O_2$ concentration target away from potentially unsafe operating conditions.
- A small impulse perturbation of the fuel servo is imposed at prescribed interval, to verify the potential onset of CO formation. This improves the algorithm performance remarkably, avoiding high CO spikes and associated upwards modifications of the $O_2$ target.

It should be noted that the adopted control architecture allows failsafe operation:

- When in CO/O2 trim operation, the algorithm relies on the availability of information on CO concentration. In case a CO sensor malfunctioning occurs, the adjustment of the $O_2$ target immediately stops and the system can revert back to O2 trim operation mode.
- In case of a malfunctioning which compromises the $O_2$ concentration signal, the system can suspend all trimming functions and revert to standard parallel positioning mode (open loop control) which uses commissioning values to determine the air and fuel servo position for a given firing rate.
- The PPC4000 has also the capability to impose limits to the maximum amplitude of the trim signal, so that air flow cannot be excessively increased or reduced causing malfunctioning and potentially unsafe conditions.

Operation of the new control algorithm was tested following a two-step approach. First, rapid prototyping was used to verify the algorithm functionality. A virtual representation of the controller was implemented in LabView to drive the actual air and fuel servomechanisms on Fireye's experimental boiler (Figure 5). A lab grade gas analyzer was used to collect information on oxygen and carbon monoxide concentrations. Through rapid prototyping, quick changes and refinements of the algorithm were possible, leading to the final version of the algorithm, ready for implementation to the target platform. Specifically, the following was tested during the rapid prototyping phase between November 2010 and March 2011:

- The evaluation of different candidate control options, enabling final selection.
- The integration with Fireye process control and flame scanner, a necessary step towards application at the demonstration site.
- The quantification of expected peak CO emission and preliminary verification of algorithm safety and robustness.
- The verification of the intended algorithm functionality independently on the final implementation (Figure 6).

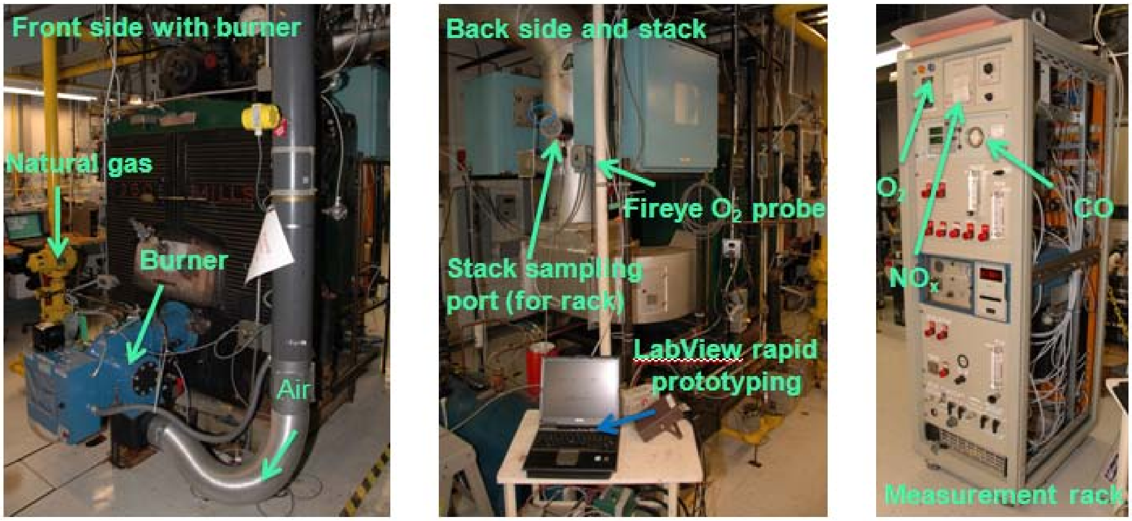



Figure 5 – Set up for rapid prototyping and algorithm testing at Fireye

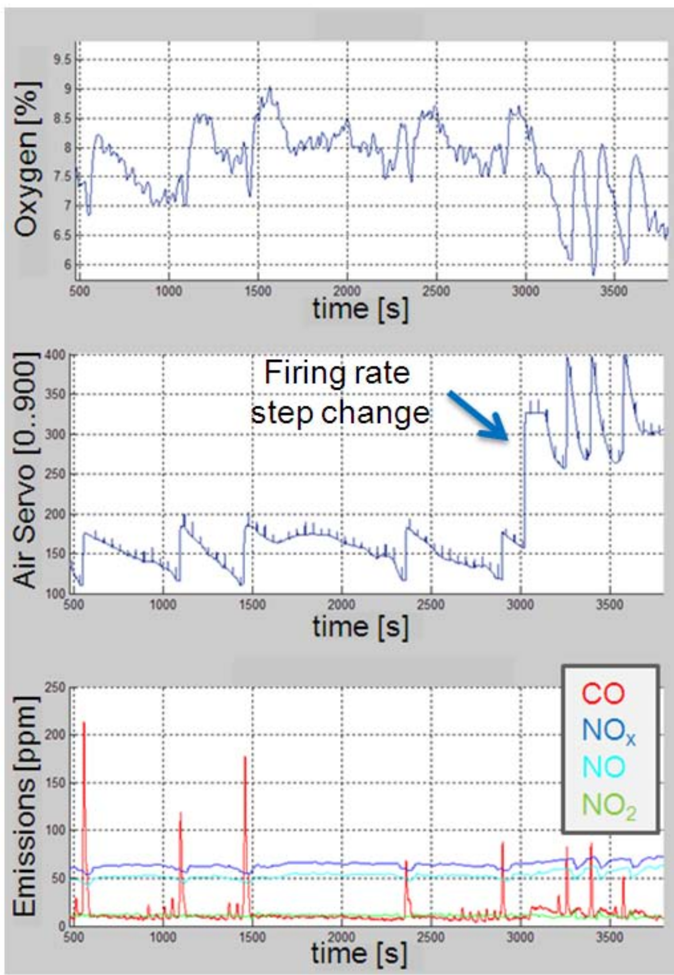



Figure 6 – Prototype application on Fireye's experimental boiler: the algorithm adjusts the air servo towards lower oxygen levels until a CO spike is detected. Then, the air servo is opened.

The final algorithm was then coded for implementation on the existing PPC4000 platform and tested to ensure correct and safe operation. Implementation on the target platform was based on a modular, object oriented architecture (Figure 7) to ensure reusability and full integration with the existing software.

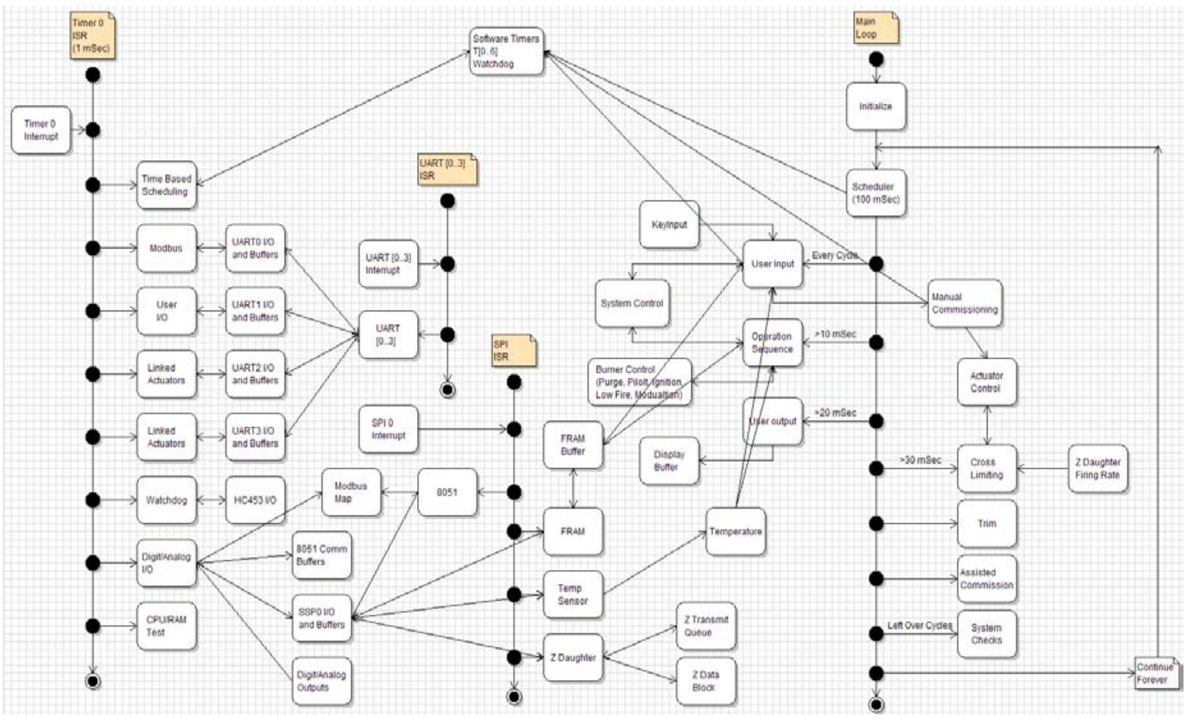


Figure 7 – Modular architecture representation of final software implementation

Testing was executed first on a bench simulator (Figure 8) enabling open loop verification and then directly on Fireye's experimental boiler in closed loop configuration (Figure 9).

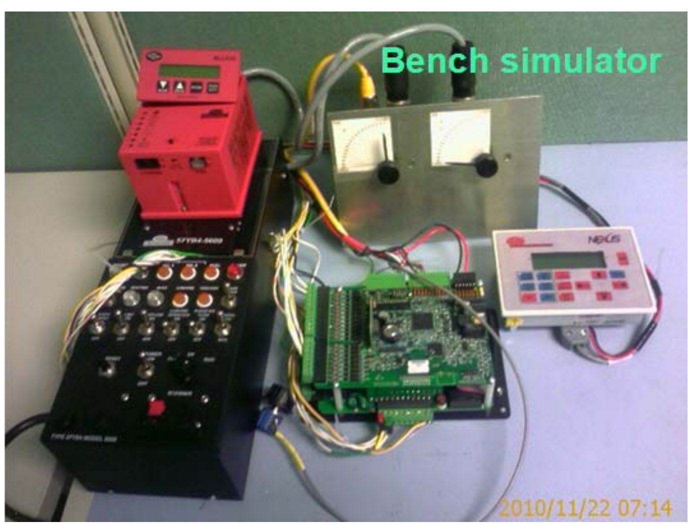


Figure 8 – The bench simulator used for open loop testing of the algorithm

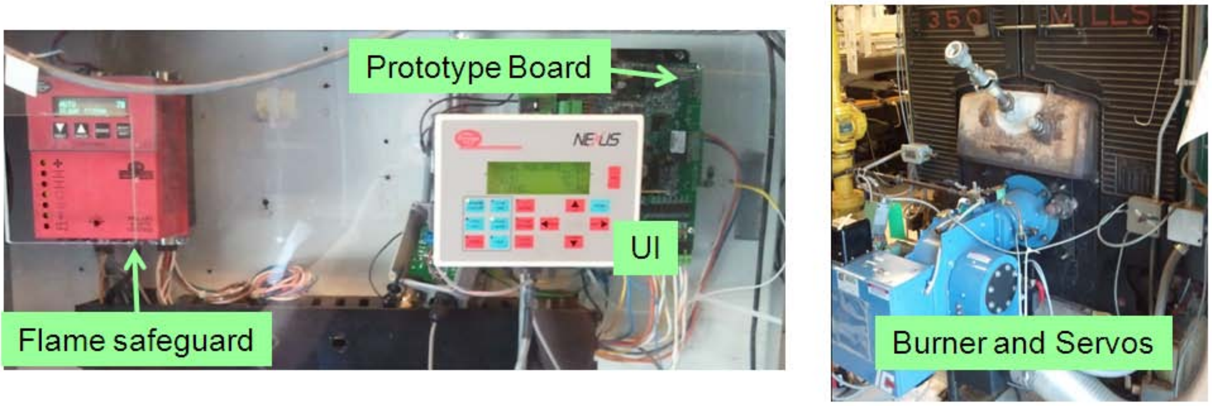
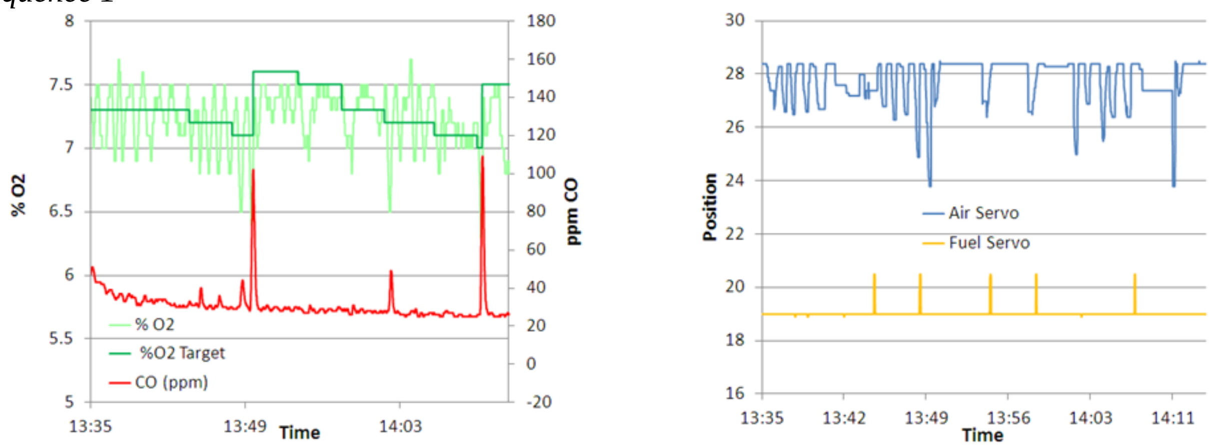



Figure 9 – The prototype being tested in closed loop configuration on Fireye's boiler

*Sequence 1*




*Sequence 2*

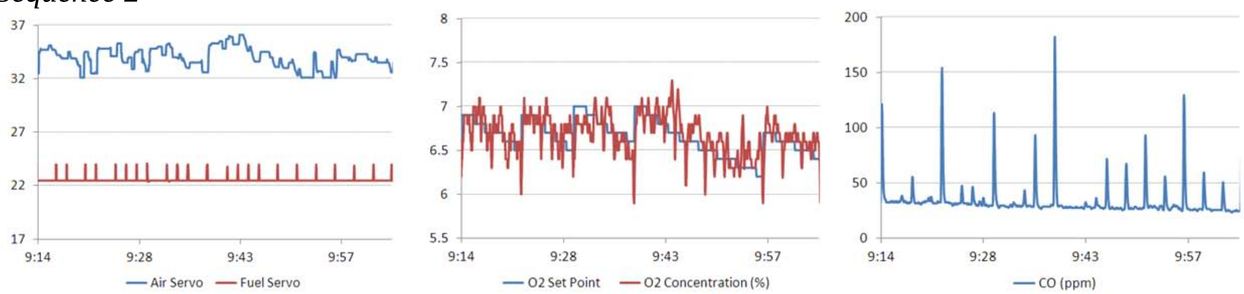



Figure 10 – Closed loop testing of prototype: sample test sequences. The algorithm responds correctly to CO spikes by increasing the $O_2$ target level

Figure 10 reports two sequences of tests used to verify the correct functional implementation of the algorithm. The algorithm seeks for the lowest possible oxygen level thereby increasing combustion efficiency by enabling operation closer to the stoichiometric point. The fuel is periodically pulsed to verify the onset of CO formation. When a CO spike is detected, the $O_2$ target is increased and air servo opens to ensure operation away from conditions where CO formation occurs.

In addition to verification testing, an extensive Failure Mode and Effect Analysis (FMEA) was conducted by the team to determine possible causes of failure of the algorithm and make provisions in the final implementation to handle such conditions in a failsafe manner. Table 1 reports the main failure modes identified and the solutions adopted to mitigate the occurrence and impact of potential failures.

Table 1 - FMEA: Identification of failure modes and implemented controls

| Device | Function | Potential Failure | Potential Effects | Potential Causes | Initial Controls | Risk priority* | Controls Added for Demonstration |
|---|---|---|---|---|---|---|---|
| **Exhaust Gas Sensors** | Controls CO in exhaust | Failure (malfunction) of the CO Sensor | Erroneous high signal. | 1. Chemical poisoning<br>2. Bad SW calibration<br>3. Sensor drift<br>4. Poor temp regulation | No controls in place; only suggested maintenance intervals | 25 | • Redundancy of CO measurements via UTRC lab grade sensor rack. |
| | | | Erroneous low signal. | 1. Chemical / physical poisoning<br>2. Bad SW calibration<br>3. Sensor drift<br>4. Poor temp regulation | No controls in place; only suggested maintenance Intervals | 225 | • Used Fireye's new sensor box with embedded CO sensing redundancy and alarming features.<br>• Redundancy of CO measurements via UTRC lab grade sensor rack. |
| | | | Out of Limits | poor cal or drift | No controls in place | 54 | SW detects out of limit condition and adjusts O2 trim within limits of operation<br>Drift was manually checked and recalibration performed at every visit |
| | | | Loss of flow to sensor | 1. Bad tubing or fittings<br>2. Plugged filter or sample line from stack<br>3. Failing pump<br>4. Open cal port | No controls in place | 135 | No control was in place to check flow to sensor box. Operation of prototype was always supervised to ensure safety and visual monitoring. |
| | | | Loss of signal or communication | 1. Poor connectivity<br>2. Loss of PLC<br>3. Loss of electric power to cell | No controls in place | 45 | SW captures this failure mode and switches operation to O2 trim. |
| | Monitor NOx in exhaust | Failure (malfunction) of the NOx Sensor | Erroneous high signal. | 1. Chemical / physical poisoning<br>2. Bad SW calibration<br>3. Sensor drift<br>4. Poor temp regulation | No controls in place; only suggested maintenance intervals | 9 | Not a safety critical function. Redundancy of measurements allows adequate capturing of signal. |
| | | | Erroneous low signal. | 1. Chemical / physical poisoning<br>2. Bad SW calibration<br>3. Sensor drift<br>4. Poor temp regulation | No controls in place; only suggested maintenance intervals | 27 | Not a safety critical function. Redundancy of measurements allows adequate capturing of signal. |

| Device | Function | Potential Failure | Potential Effects | Potential Causes | Initial Controls | Risk priority* | Controls Added for Demonstration |
|---|---|---|---|---|---|---|---|
| | | | Out of Limits | poor cal or drift | No controls in place | 18 | Not a safety critical function. |
| | | | Loss of flow to sensor | 1. Bad tubing or fittings<br>2. Plugged filter or sample line from stack<br>3. Failing pump<br>4. Open cal port | | 27 | Not a safety critical function. |
| | | | Loss of signal or communication | 1. Poor connectivity<br>2. Loss of PLC<br>3. Loss of electric power to the heater | | 15 | Not a safety critical function. |
| | Monitor O2 in exhaust | Failure (malfunction) of the O2 Sensor | Erroneous high signal. | 1. Chemical / physical poisoning<br>2. Bad SW calibration<br>3. Sensor drift<br>4. Poor temp regulation | No controls in place; only suggested maint. Intervals | 12 | Leverage diagnostics of existing PPC4000 O2 trim platform, which is UL certified.<br>Redundant O2 sensors to validate measurements. |
| | | | Erroneous low signal. | 1. Chemical / physical poisoning<br>2. Bad SW calibration<br>3. Sensor drift<br>4. Poor temp regulation | No controls in place; only suggested maint. Intervals | 12 | Leverage diagnostics of existing PPC4000 O2 trim platform, which is UL certified.<br>Redundant O2 sensors to validate measurements. |
| | | | Out of Limits | poor cal or drift | No controls in place | 12 | Leverage diagnostics of existing PPC4000 O2 trim platform, which is UL certified.<br>Redundant O2 sensors to validate measurements. |
| | | | Loss of flow to sensor | 1. Bad tubing or fittings<br>2. Plugged filter or sample line from stack<br>3. Failing pump<br>4. Open cal port | | 18 | Leverage diagnostics of existing PPC4000 O2 trim platform, which is UL certified.<br>Redundant O2 sensors to validate measurements. |
| | | | Loss of signal or communication | 1. Poor connectivity<br>2. Loss of PLC<br>3. Loss of electric power to the heater | | 10 | Leverage diagnostics of existing PPC4000 O2 trim platform, which is UL certified.<br>Redundant O2 sensors to validate measurements. |
| **Trim SW** | Controls Air/ Fuel | Parameter grossly mistuned | Eff. Degradation<br>Emission spikes<br>Servo life<br>Failure of boiler | Sensor failure (O2 or CO)<br>Fuel Heating Value variations<br>Plant parameter changes (i.e. mechanical equipment, etc.)<br>Look-up table corrupted | limits are write-protected | 32 | O2 trim: safety is guaranteed by high O2 set point margins and limitation on air servo trim range.<br>CO/O2 trim: control prototype is never left unattended, visual monitoring and limits on trim functions are active. Additionally, tuning phase of controller was conducted to verify effects on response. |

| Device | Function | Potential Failure | Potential Effects | Potential Causes | Initial Controls | Risk priority* | Controls Added for Demonstration |
|---|---|---|---|---|---|---|---|
| | | Parameters slight to moderately mistuned | Eff. Degradation<br>Emission spikes<br>Servo life<br>Failure of boiler | Plant parameter changes (i.e. mechanical equipment, etc.)<br>Look-up table corrupted or data entered incorrectly | | 50 | O2 trim: safety is guaranteed by high O2 set point margins and limitation on air servo trim range.<br>CO/O2 trim: control prototype is never left unattended, visual monitoring and limits on trim functions are active. |

* The risk priority level is calculated as a product of a severity index, a probability of occurrence factor, and the capability of detection of a failure before it impacts operation.

### 2.2.2 The Gas Sensing Device

Selection of low cost but accurate, reliable and durable sensing devices to continuously measure the concentrations of $O_2$, CO, and $NO_x$ in the boiler exhaust is critical to enable reliable monitoring and feedback control of combustion for optimal boiler efficiency and minimum environmental impact. In addition, packaging and integration of the sensors into the system must be carefully carried out to ensure measurement reliability in a harsh environment characterized by high temperature and, in case of oil fired systems, of soot formation in the exhaust. Finally, the sensor characteristics and placement must be selected to ensure adequate response time for the controller to react promptly to changing settings and environmental effects. For the purposes of continuous monitoring and closed loop control, three separate devices were deployed at the demonstration site:

1. A multi sensor device enabling continuous monitoring of CO, $O_2$, and $NO_x$ (for brevity, “Forney box”). The device was an existing prototype acquired from Fireye and previously tested in a power plant setting. Under this program, new sensors were installed as well as consumable materials, and a thorough performance test was conducted at UTRC to check accuracy, response, drift, and CO, $O_2$, and $NO_x$ cross-sensitivity. The device was used for closed loop testing at Fireye and was later installed at Watervliet Arsenal to provide gas monitoring.
2. A second multi-sensor device provided by Fireye enabling sensing of CO and $O_2$ (“Fireye box”). This 2$^{nd}$ generation device was fully developed and tested by Fireye outside of the scope of the project and was provided for closed loop control at Watervliet Arsenal.
3. A continuous CO monitoring device entirely developed under this program with the objective of evaluating a sensing technology (non dispersive infrared) with lower technology maturity but expected improved performance and serviceability (“NDIR box”).

For all the devices, accuracy, drift, cross-sensitivity, and response time were key parameters to evaluate to ensure satisfactory operation in a closed loop setting. While response times of 5 seconds are required for $O_2$ measurement systems to allow the controller to promptly act, the sensor response time for $NO_x$ and CO could be extended more than 30 s as CO-based corrections of the $O_2$ reference value are typically performed within a timescale of minutes.

*The “Forney box”*: Effective gas extraction, conditioning, and feed into the gas sensors were achieved by using a gas probe enabling extraction of exhaust gas and measurements of $O_2$, $NO_x$,

and CO. The device is comprised of components for reduction of water content, elimination of soot and sulfur which could contaminate the sensors, and an apparatus to maintain stable environmental conditions. Some of the components require replacement of filter material used for scrubbing sulfur and $NO_x$ from the gas feed into the CO sensor, thus avoiding undesired cross-sensitivity effects. Provisions are also made to enable installation of the sensor analysis package in proximity of the stack to minimize gas transport time. Measurements of $O_2$ and $NO_x$ are obtained by means of automotive grade yttria-stabilized zirconia sensors. This solution combines good sensitivity at reduced compared to today's commercially available in situ $O_2$ sensing. Electrochemical sensors for CO monitoring were selected because of their low cost, long life, high sensitivity, and robustness.

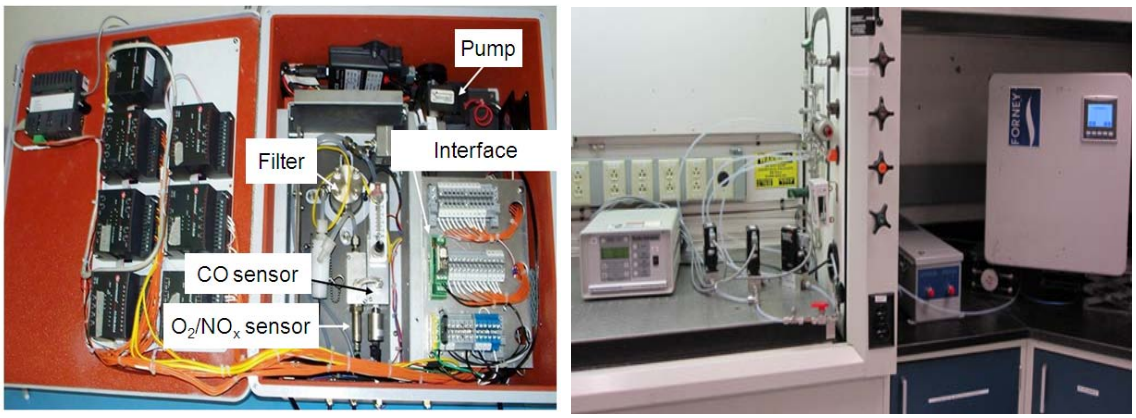



Figure 11 – The "Forney box" multi-sensor device components and the UTRC testing set up

Extensive testing on boiler enabled to confirm the viability of the approach. The following tests were performed for the CO and $NO_x$ sensors:

- Linearity measurement for $NO_x$ and CO to verify accuracy;
- Time response tests to verify applicability for closed loop use;
- Cross sensitivity to verify the absence of false response of the sensors.

Testing of the $O_2$ sensors was not performed as the used device is the same adopted in the current PPC4000 product. The following test protocol was used for qualification of the Forney box:

1. Gases were mixed to reach target concentration(s), i.e. CO in air (1000 ppmv) mixed with bottled compressed air, Pure $O_2$ mixed with pure $N_2$, NO in $N_2$ mixed with bottled compressed air, and pure $CO_2$ mixed with bottled compressed air.
2. Three mass flow controllers were used to regulate the amount of gas flow into the box. All mass flow controllers were calibrated against a Gilibrator calibration source;
3. Three minute waits between readings for the detectors to stabilize for each gas concentration.

Results of the qualification process are reported below. Overall, very good accuracy (less than 7% deviation from known concentration levels, Figure 12) was found for both sensors, as well as the absence of cross sensitivity effects (Figure 13to Figure 15). The time of response of the CO sensor was about 45 s (due primarily to the presence of the $NO_x$ scrubber), which is acceptable for applicability in closed loop configurations (Figure 16).

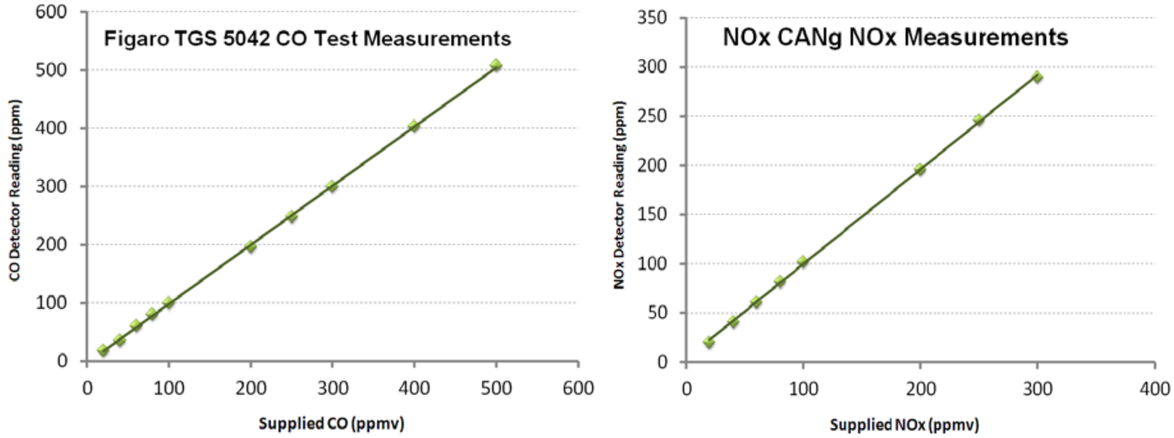



Figure 12 – Linearity test for the CO and $NO_x$ sensors within the range of interest.

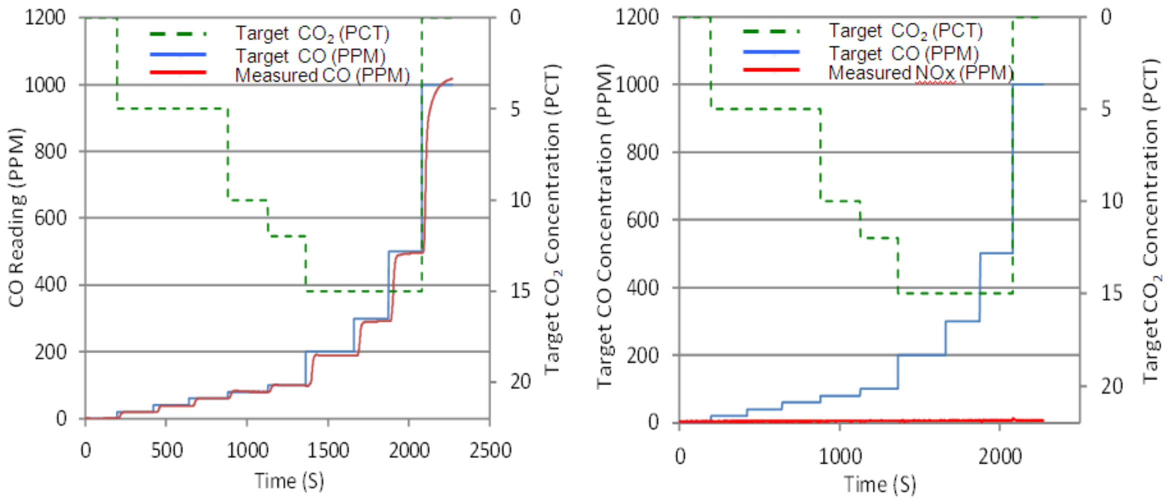
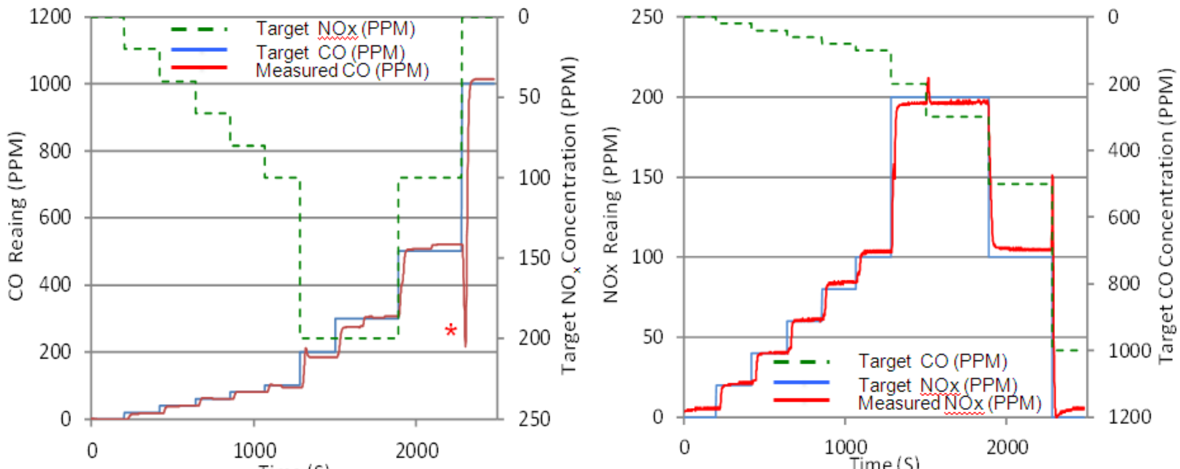



Figure 13 – Cross sensitivity of CO and $NO_x$ measurements for varying CO and $CO_2$ concentrations.




*: The dip is due to changing gas composition operation, which is temporary.

Figure 14 – Cross sensitivity of CO and $NO_x$ measurements for varying $NO_x$ and CO concentrations.

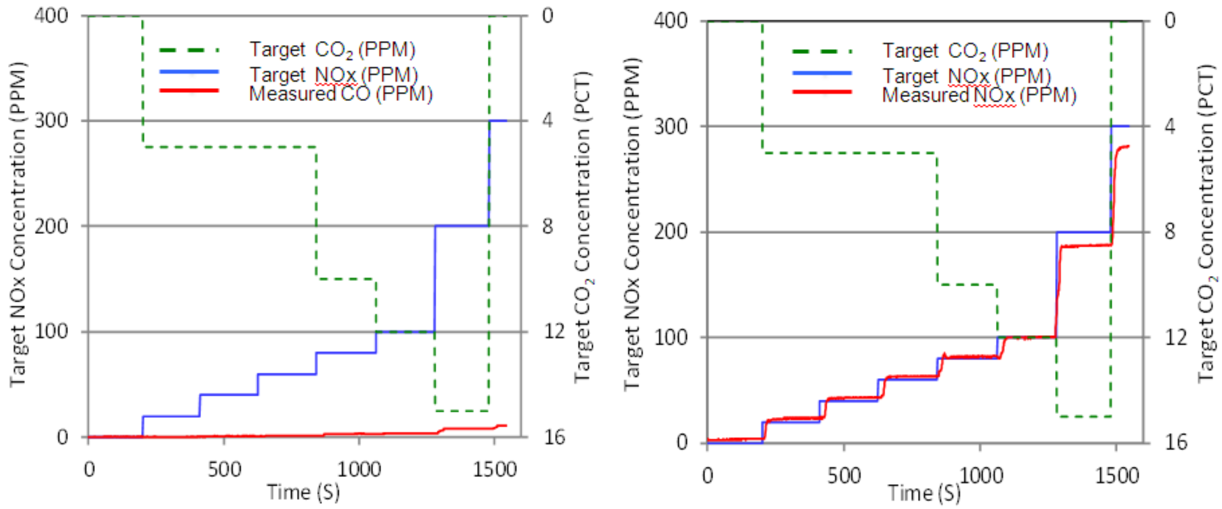



Figure 15 – Cross sensitivity of CO and $NO_x$ measurements for varying CO and $NO_x$ concentrations.

Cross sensitivity tests led to the following conclusions:

- The $CO/CO_2$ mixture produced a $NO_x$ reading below 7 ppm for all measurements, while the CO sensor error was <3% over the whole range, same as without $NO_x$.
- The $CO/NO_x$ mixture produced led to CO readings with < 4% error over the [40,1000] ppm range, and the $NO_x$ readings with < 5% error over the [40,200] ppm range.
- The $CO_2/NO_x$ mixture led to CO readings below 11 ppm during the experiment, and the NOx sensor showed < 6% error over the [60,300] ppm range.

These results were acceptable relative to the desired accuracy requirements (for control purposes, the detection of sudden changes of CO peak concentrations is essential, vs. accurate assessment of the actual concentration).

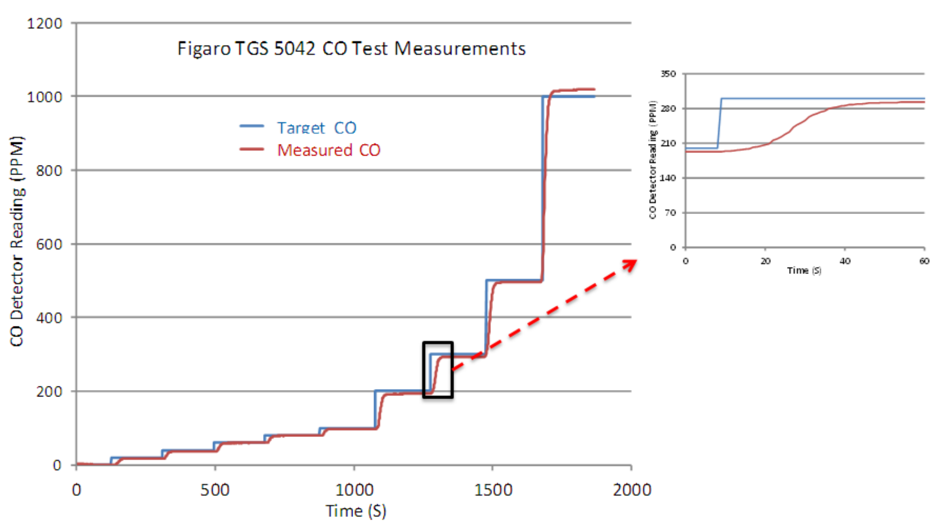



Figure 16 – Time response of CO sensor to step variation of CO concentration is about 45 s.

*The "Fireye box"*: For control closed loop purposes, as part of their product development efforts Fireye developed a second generation $CO/O_2$ multi-sensor sensor device based on technology analogous to that of the Forney box. Because of the low cost of CO electrochemical sensors, the box design included redundant CO measurements for improved reliability. Accuracy and time responses were analogous to those of the Forney box. Fireye conducted qualification activities on a customer boiler site prior to deployment at Watervliet Arsenal (Figure 17).

Figure 17 – The Fireye box, used for CO and $O_2$ monitoring and closed loop control.

*The "NDIR box"*: The identification of alternative approaches to CO measurements arises from the need of improved accuracy as well as the reduction of maintenance and replacement costs associated with the use of the CO electrochemical cells. While CO electrochemical sensors are inexpensive, they require removal of $NO_x$, $SO_x$, and other impurities which is accomplished by introducing a scrubber filter at the sensor chamber inlet. Periodic replacement of the filter would be required; hence an additional maintenance task. A new generation of sensors which use non-dispersive infrared (NDIR) technology was considered for application and demonstration at the boiler site. The advantages of the NDIR technology are: increased accuracy, faster response time, no cross-sensitivity to $NO_x$, less maintenance, as well as the elimination of the scrubber filter. The following steps were pursued in maturing the NDIR sensing approach to TRL4/5:

1. Selection of the NDIR sensor and qualification;
2. Integration in a sensor package for gas treatment, necessary for deployment at a boiler site;
3. Testing of the new sensor package;

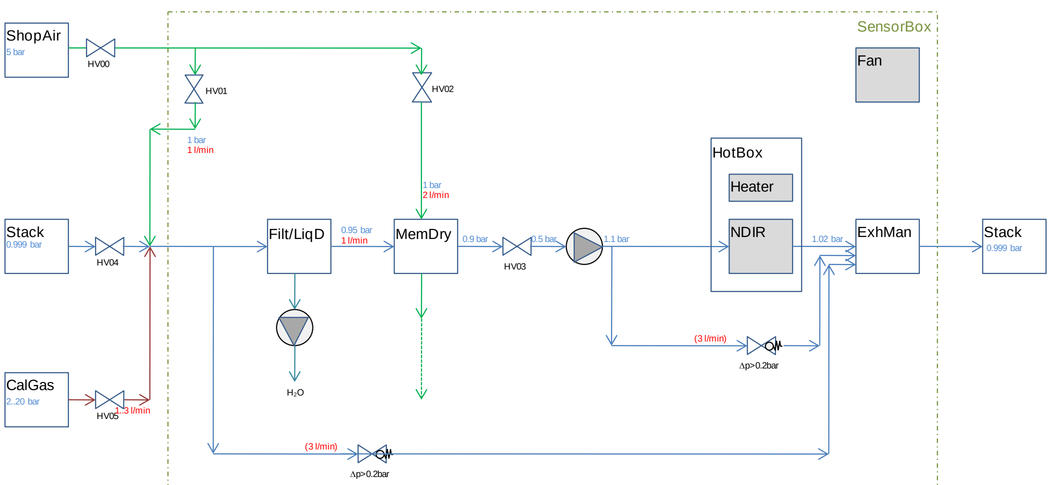
*Selection & qualification*: While there were several companies that offered Non-Dispersive Infrared (NDIR) technology for the detection of CO; there was only one supplier (Sensors, Inc, Saline, MI, www.sensors-inc.com) that had an available product with automotive grade/costs and measured as low as 1000 ppmv with 100 ppmv resolution. This sensing platform is used to monitor automotive CO emissions, and is marketed as a low cost diagnostic device.

Working closely with Sensors, Inc. engineers, UTRC transitioned this technology to TRL4/5 by: incorporating environmental controls to reduce drift, improving light output to increase signal-to-noise ratio and hence resolution, referencing the output to air to improve absolute accuracy, and

eliminated water and contaminates to ensure durability. Upon completion of this effort, the commercial-off-the-shelf technology was shown to be capable of responding to concentrations as low as 10 ppmv with $\pm$1 ppmv resolution. Final maturation to TRL6 was not undertaken as part of this effort as the *Fireye* sensor box proved suitable for control and thus further improvements will be left to the supplier.


Figure 18 – Testing rig for the NDIR sensor.

*Integration*. For the NDIR sensing system to be suitable for measurement of CO concentrations in the boiler exhaust, it is necessary to pre-process the flue. Indeed, the NDIR sensor is able to provide correct measurements provided that water vapor is completely eliminated, and drift to temperature, lamp aging, and detector variability are eliminated. For these reasons, a sampling and conditioning system was designed for the sensor to enable reliable use in a boiler room setting. The design of the sensor system is reported in Figure 19.




**Sensors:**
FT: Flow Transmitter
LS: Liquid slip sensor
PT: Pressure
RH: Rel. humidity
TE: Temperature

**Actuators:**
BLO: Blower
CV: Control Valve (automatic, continuous)
HV: Hand Valve (aka “Flow Control”)
PMP: Pump
SV: Solenoid Valve (on/off)

Figure 19 – Schematic of the sensor system for gas conditioning

The operation of the sensor at the desired operation temperature is ensured by an enclosure (HotBox) with controlled temperature. The gas sample is drawn into the sensor by means of a pump. Water vapor from the sample is eliminated by means of a drying membrane, whereas water in liquid form is eliminated upstream by a condensing device. Provisions for flushing the system (with shop air or dry nitrogen) and for sensor calibration are made.

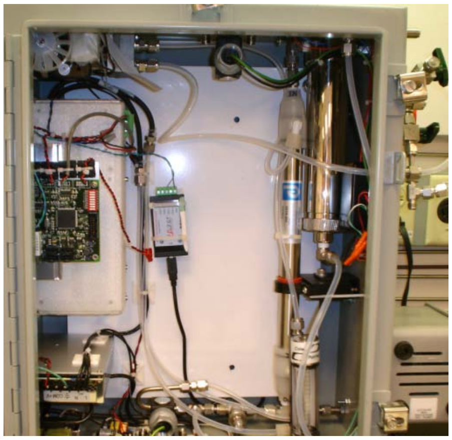


Figure 20 –Final design of the NDIR sensor box.

*Testing*. Linearity tests were performed for the system, to verify accuracy of the measurement. An error of less than 11 ppm was observed for the range within 10-300 ppm and less than 40 ppm error was observed for the interval between 500-1000 ppm, which is acceptable for control purposes (Figure 21). Cross sensitivity tests, conducted with a mix of three gases (CO, $CO_2$, and $C_3H_8$) demonstrated that the NDIR sensor was clearly able to separate out the effects and compensate response for any cross-sensitivity.
The verification of long term drift was not possible in a laboratory setting and it was decided to perform them as part of the demonstration plan at Watervliet Arsenal.

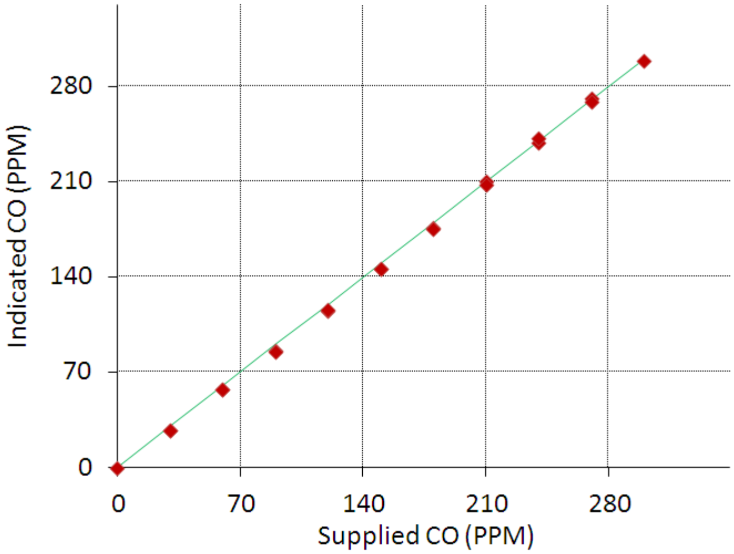



Figure 21 –Accuracy measurement for imposed CO concentration.

### 2.2.3 The Graphical User Interface

Monitoring of the boiler, including operation status and performance was introduced to assist the boiler operator in verifying the potential of energy savings, compliance with emissions, and ensure correct operation. A graphical user interface (GUI) was specified, designed and implemented as part of the demonstration. The selection of Automated Logic Corporation's WebCTRL as data acquisition system allowed to leverage the graphical interfacing feature of a building management system to read and display information from the PPC4000 controller. Connectivity with the PPC4000 was implemented via the MODBUS protocol for communication with the data acquisition module, connected via BACnet to a laptop computer used as web server. The ALC interface is displayed on a web browser by means of a simple URL call and login procedure.

The following requirements were defined:

- The visualization package should be designed as a PC-based graphical user interface, preferentially within a web-based interface.
- The GUI environment should be designed to display all systems operating parameter necessary for a boiler operator to verify the systems performance of the boiler. The different physical streams (fuel, water, air…) should be displayed with a well defined color coding convention.
- The GUI must have three main display screens illustrating (1) the current boiler operation online, (2) historical and actual data on fuel usage, steam production, & emissions. Compound data as well as (3) time charts displaying trends had to be included.

Figure 22 –The laptop displaying the GUI for visualization of boiler operation.

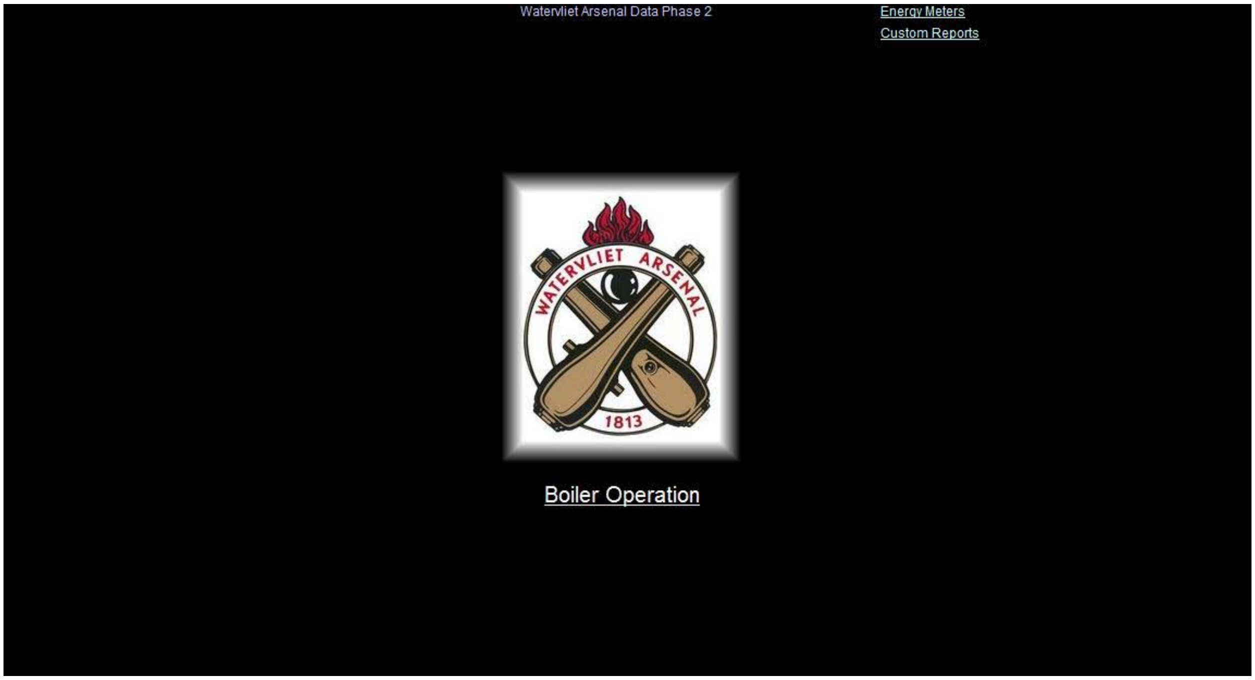



Figure 23 –The GUI: boiler operation view.

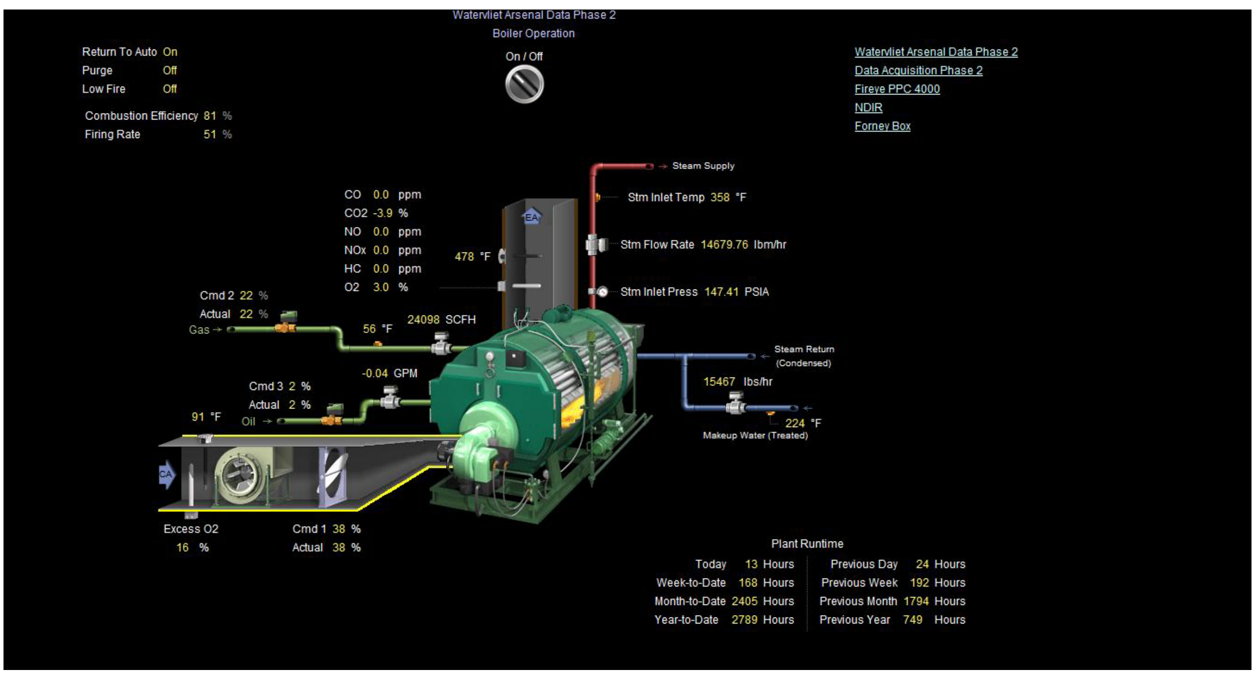



Figure 24 –The GUI: boiler operation view.


Figure 25 – The GUI: boiler operation summary view.


Figure 26 – The GUI: utilities view.

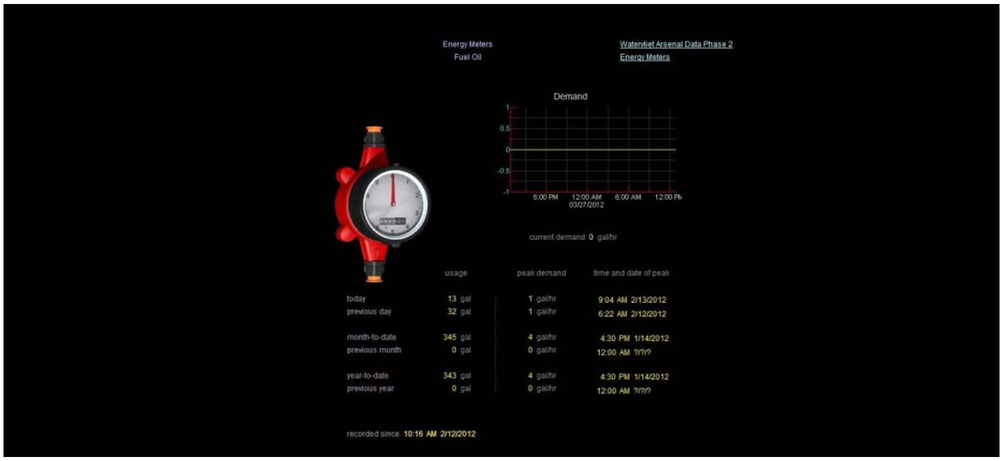



Figure 27 – The GUI: utilities view – detail on specific fuel.

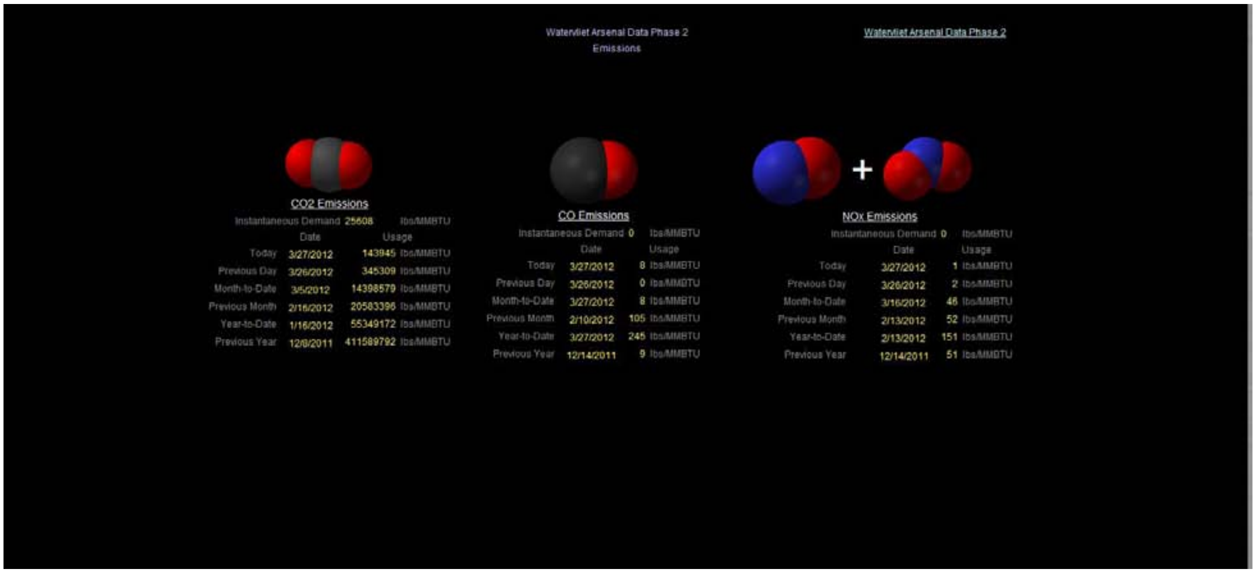



Figure 28 –The GUI: emissions view.

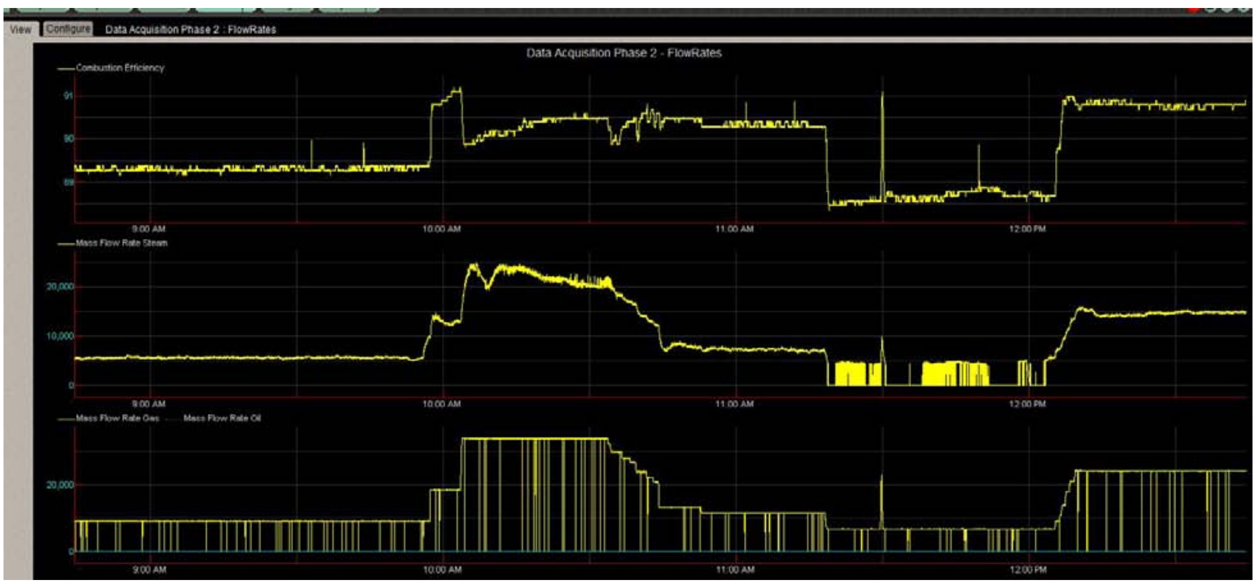



Figure 29 –The GUI: trending capability.

The physical implementation of the GUI at Watervliet Arsenal on a laptop platform is reported in Figure 22, whereas screen shots of the three main views conforming to the requirements specified above are reported in Figure 24 to Figure 28.

## 2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The demonstrated technology enables fuel savings while ensuring the boiler always operates in safe conditions. Fuel efficiency improvements translate directly into reduced $CO_2$ emissions and fuel costs, which represent the main driver of the total operating costs of a boiler. By directly measuring concentrations of $O_2$, CO, $NO_x$ the technology enables continuous monitoring of key

exhaust gas species leading to environmentally friendly operation and providing indicators to boiler operator of the need for maintenance. Additional benefits of the technology include robust operation in face of variability of environmental conditions and system degradation, adaptability to different boiler and oil/gas burner configurations, extensibility to operation with nonconventional fuels (e.g. biogas and syngas).

Applicability of the technology is limited to single burner, non-condensing boilers fueled with gaseous or liquid fuel with capacity between 10 and 100 MMBtu/h. As boiler size increases, multiple burners are used in a single combustion chamber, making the technology insufficient to provide individual burner controls. Indeed, exhaust gases from each burner mix, so that stack measurements do not carry information on each burner's combustion efficiency. Large, single burner boilers use flow metering instead of simple positioning for air and fuel supply (fully metered controls). Modifications to the technology to include fully metered systems are possible. The technology can be implemented on smaller size boilers, but it may not be an attractive investment because of high first costs in relation to achievable fuel savings. The technology does not address the direct control of emissions and treatment of flue gases.

Expected efficiency improvements are generally of the order of 4-7% for noncondensing boilers typically operating below or slightly above 80%. Higher efficiency improvements can certainly be obtained via boiler replacement and adoption of condensing systems often operating above 90%. Full boiler replacement however requires a greater investment, order of magnitudes higher than a control system upgrade. Whether full boiler or control system upgrade is preferable would mostly depend on availability of capital investment and the need of a complete infrastructural overhaul, for example a migration from a centralized to a decentralized architecture of the heating system, from oil to natural gas, or from conventional to part renewable. It should be noted that, because of the short payback time, combustion control overhaul can provide short term benefits even if a heating plant update is expected later.

Technology feasibility relies on the availability of robust, low-cost gas species sensing components. As this is a relatively quickly evolving field (certainly compared to boiler technology), it is expected that costs will drop and more COTS sensors with the required accuracy and reliability will enter the market over the next few years. Particularly, the demonstration also aimed at testing new NDIR technology for CO sensing that might be too costly today but for which a path to cost reduction exists via system optimization and mass production. We anticipate that future product enhancements will leverage new sensors based on emerging technologies with improved performance (e.g. drift compensation, faster response, and reduced maintenance) at an even more reduced cost while allowing sufficient component flexibility.

During the demonstration, it was noted that the algorithm is effectively able to maintain operation close to stoichiometric conditions by sensing the insurgence of CO spikes, therefore maintaining safe operation at the highest possible efficiency. This translates into significant improvement in terms of efficiency, especially at low firing rate conditions, where $O_2$ trim systems are typically commissioned in a conservative fashion imposing high $O_2$ target levels. On the other hand, the $CO/O_2$ trim technology adds some complexity to the commissioning of the boiler, as it requires:

- A new mindset: the installer should set commissioning points at lower oxygen target levels than for an O2 trim system.
- Tuning of additional parameters which determine the amplitude of fuel pulses and thresholds for triggering adjustments of the target O2 levels.
- Very careful tuning of the air trim proportional-integral (PI) controller. Indeed, the CO/O2 trim works adequately only if the PI is tuned so that the system does not react to rapid changes of O2 and CO concentrations, and does not generate unwanted oscillations of the O2 concentration. Gross mistuning of controller parameters can lead to reduced performance in terms of efficiency gains.

Benefits and drawbacks of the demonstration technology are summarized in Table 2.

Table 2 – Table of benefits and drawbacks

| | **Description** | **Typical excess $O_2$** | **Benefits** | **Drawbacks** |
|---|---|---|---|---|
| **Legacy** | Fuel and air positioning set by means of mechanical linkage. Flue gas composition not measured. | 8% | Low cost, familiar technology. | Large safety margin on excess $O_2$, performance drift due to linkage degradation, no emission monitoring. |
| **SoA** | Replacement of linkage with parallel positioning of inlet fuel and air. Flue gas $O_2$ concentration measured to trim excess air. | 4% | Precise fuel and air modulation, lower excess air required, excess air is controlled and maintained. | Wide safety margin required to account for variable environment conditions and part load operation, especially at lower firing rates. No emission monitoring, high cost. |
| **Demonstration** | Parallel positioning system using measurements of flue gas CO and $NO_x$ concentrations in addition to $O_2$. Availability of assisted commissioning feature for boiler tuning and setup. | 2% | Detects unsafe operation via direct CO monitoring, improves part load performance, monitors and responds to high emissions. Adapts to degradation, changing conditions and fuel properties. | Cost of additional sensing devices (to be reduced by leveraging sensors from automotive applications). Need for more careful tuning of the system parameters to ensure efficiency gains. |

# 3. PERFORMANCE OBJECTIVES

Table 3 – Performance Objectives

| Performance Objective | Metric | Data Requirements | Pre-demonstration Success Criteria |
|---|---|---|---|
| **Quantitative Performance Objectives** | | | |
| Improve Energy Efficiency | Short and long-term fuel to steam efficiency | Measurement of fuel and steam flow rates | >5% improvement over baseline;<br>>1.8% improvement over SoA |
| Reduce Carbon Emissions | Short and long-term fuel to steam efficiency | Measurement of fuel and steam flow rates | >5% improvement over baseline;<br>>1.8% improvement over SoA |
| Increase combustion efficiency | Combustion efficiency over entire operating envelope (firing range) | Measurement of fuel flow rates, inlet air and stack temperature and gas composition | >6% improvement over baseline;<br>>2% improvement over SoA |
| Meet CO, $NO_x$ regulatory emission requirements | Measured exhaust gas composition (CO, $NO_x$) | Continuous measurement of stack gas composition | Meet or exceed emission targets. |
| Reduce controls commissioning time | Measured time to set air/fuel positions over boiler firing range | Commissioning times during commissioning sessions for state of the art and new concept | 30% reduction over baseline |
| Reduce system operating costs | fuel costs, yearly operating costs for maintenance, tuning and commissioning | Fuel savings performance calculations, plus estimates provided by Fireye or other installer for maintenance and replacement costs of critical parts | >5% improvement over baseline;<br>>1.8% improvement over SoA |
| Verify sensor reliability | measurement errors and drift over time | Component testing of sensors prior to deployment; Calibration of sensors pre and post demonstration; Sensor failures during demonstration | Drift of sensors (CO, $NO_x$) less than 5%/demo period (full range), no failures during demonstration time |
| Ensure system availability | Equipment operational or ready to operate | Recording of all downtime after installation has been completed | >95% after installation completed (for prototype) |
| Evaluate Years to Payback | NIST building lifecycle program | First cost of components. Estimates of typical installation costs; Assumed typical yearly load profile | <1 year (typical 25MMbut/h boiler) |
| | | | |
| **Qualitative Performance Objectives** | | | |
| Ensure ease of installation and configuration | Ability of average service technician to configure and deploy successfully | Feedback from commissioning agent on ease-of-use and required time | a single service technician able to deploy at least as quickly as 'baseline' or 'SoA' |

| Performance Objective | Metric | Data Requirements | Pre-demonstration Success Criteria |
|---|---|---|---|
| Ensure ease of use for boiler operator | Ability of average boiler operator to use interface effectively and achieve necessary daily operational changes | Feedback from boiler operator after training and a few weeks of experience in using the new system | boiler operators understanding features and able to take action for all regularly occurring events |
| Ensure system maintainability | Number of service calls and parts replacements | Estimated effort for baseline system and higher efficiency systems | Within expectations of typical operator |

Each performance objective presented in Table 3 is described in detail as follows.

## 3.1 QUANTITATIVE PERFORMANCE OBJECTIVES

***Objective 1 – Improve energy efficiency***. Boiler energy efficiency is defined as 'fuel-to-steam' efficiency, or the ratio of the energy spent to make steam and the heating energy stored in the fuel. This metric is associated with fuel cost savings and operating costs savings. Although several factors contribute to boiler efficiency (e.g. boiler and burner type and age, maintenance and operating conditions), we focused on boiler efficiency improvements associated with the introduction of the demonstration technology. All other factors under our control remained unchanged during demonstration. In the absence of measured boiler performance data at the start of the program, for threshold assessment purpose, it was assumed that the original linkage based system operated around 8% exhaust gas oxygen at full load (which turned out to be higher than actual values recorded). Also, actual baseline efficiency conditions using both natural gas and oil fuels was calculated and reported. The following targets were projected:

- Boiler efficiency (-): 5% improvement over the baseline
- Boiler efficiency (-): 1.8% improvement over state-of-the-art

There are various definitions of boiler efficiency, each specifying energy losses in different ways, depending on what information is available from measurements, and the rate at which data was taken. For this work, boiler efficiency, or fuel to steam efficiency is calculated as

Fuel to steam efficiency = useful energy output/energy input = Steam enthalpy/Fuel enthalpy

Measurements of fuel and steam flow are required for computation of boiler efficiency. Both short-term and long-term quantifications were carried out:

- To compute short-term efficiency the boiler was to be operated at 5 operating points ('Low Fire', 25%, 50%, 75% and 100%) in steady state for at least one hour (Fuel flow held constant, air flow closed-loop, steam valve fixed). By the end of testing, many more short term steady state intervals were analyzed for each control configuration. Results are presented in Section 6.
- For long-term efficiency, endurance data was to be used to compute a 'real-world' efficiency curve over the operating range, including effects like dynamics and disturbances. Extrapolation was to be used to calculate a yearly efficiency metric projecting operation during the entire heating season. As it will be seen in Section 6, boiler efficiency is calculated

for each of the steady state intervals, both short and long duration, for the entire sample set for all control schemes, and plotted against percentage of maximum fuel flow.

***Objective 2 – Reduce Carbon Emissions.*** Carbon Emission reduction ($CO_2$) is inversely proportional to boiler efficiency (objective 1). The following targets are projected:

- Emission reduction (-): 5% reduction over the baseline
- Emission reduction (-): 1.8% reduction over state-of-the-art

The test data of Objective 1 was used to compute the performance. Carbon emission reduction was calculated by applying the standard $CO_2$ carbon emission factor associated with natural gas and No. 2 fuel oil. Projected yearly emission reductions were calculated as in Objective 1.

***Objective 3 – Increase combustion efficiency***. Combustion efficiency is a measurement of performance of the combustion process independent of other factors contributing to the overall boiler efficiency. Combustion efficiency is an index of combustion completeness or the quantification of the release of usable thermal energy to the boiler. Since the demonstrated technology addresses improvements in the combustion process, it is relevant to quantify this metric. There are different formulas available for combustion efficiency, each with a specific representation of heat losses. In this report we used to one based on British Standard BS845 [BS 1987] and available in [Fireye 2005]:

$$\eta\ [\%] = 100\% - 20.9 \cdot K_{1g} \cdot T_{net} / [K_2 \cdot (20.9 - \%O_2)] - K_3 \cdot (1 + 0.001 \cdot T_{net})$$

where $20.9 \cdot K_{1g} \cdot T_{net} / (K_2 \cdot [20.9 - \%O_2)]$ represents the dry losses due to the carbon content of the fuel and $K_3 \cdot (1 + 0.001 \cdot T_{net})$ represents the wet losses due to hydrogen content. $K_{1g}$ is a constant parameter dependent on the carbon content of the fuel, $T_{net}$ ($=T_{flue}-T_{in}$) is the temperature difference between the inlet air, $T_{in}$, and the exhaust flue gas temperature, $T_{flue}$, % $O_2$ is the volumetric oxygen content of the exhaust, $K_3$ is a fuel constant relating to the conversion of the hydrogen content of the fuel to water vapor in the combustion process, and $K_2$ is the maximum theoretical $CO_2$ content. The following targets were projected:

- Combustion efficiency (-): 6% improvement over the baseline
- Combustion efficiency (-): 2% improvement over state-of-the-art

Air inlet and exhaust temperatures and $O_2$ concentration in the exhaust were directly measured. Additionally, fuel flow rate (both oil and gas) was measured to determine the firing rate enabling the computation of an efficiency curve.

***Objective 4 – Meet CO, $NO_x$ regulatory emissions requirements***. An operating permit to control air pollution from stationary sources as specified by Title V of the Clean Air Act is not required for the demonstration site due to a grandfather clause. The site still must comply with emissions limits specified under “Cap by Rule” which limits yearly emissions of $NO_x$ (and other species). For purpose of demonstration, we considered limits corresponding with current industry guidelines and complied with those. As natural gas is used most of the times, the following targets were proposed and were demonstrated during tests with natural gas:

- CO (ppm, dry): < 100
- NOx (ppm, dry): < 120

Direct measurement of emission gas species was performed as part of the demonstration technology and representative results are included.

***Objective 5 – Reduce controls commissioning time***. Reduction of commissioning time is an important element as it has an impact on first installation and maintenance costs. Automation via an assisted commissioning algorithm was initially proposed, but could not be performed due to technical problems associated with the software implementation on the PPC4000 platform. The algorithm was supposed to assist an operator with setting fuel and air positions across the boiler firing range, including low fire, high fire and ignition points. The target values are:

- Commissioning time (hours): 30% reduction over baseline (8 hours)
- Commissioning time (hours): 10% reduction over state-of-the-art

A qualified technician was to commission the linkage based system after the baseline testing and the $O_2$ trim system prior to the SoA demonstration, accurately recording time spent. In reality, only qualitative observations on commissioning could be collected during the demonstration.

***Objective 6 – Reduce system operating costs.*** Reduction of boiler operating costs is primarily achieved through fuel savings. Computation of this metric was to involve evaluation of operating costs not limited to fuel costs, but also including cost of maintenance and replacement costs. Targets are:

- Boiler operating costs ($): 5% reduction over the baseline
- Boiler operating costs ($): 1.8% reduction over state-of-the-art

Fuel costs were to be computed based on data collected for Objective 1 and cost information from local utilities. To quantify maintenance cost and estimate typical replacement costs, field information provided by Fireye for similar boiler installations and operation was used.

***Objective 7 - Verify sensor reliability.*** Sensor reliability ($O_2$, CO, and $NO_x$) was monitored during the period of testing in Watervliet. Weekly calibration was performed to measure degradation over time. Additional extended time performance testing at Fireye's customer sites was to be considered to gather additional data on sensor performance. The following targets were proposed:

- Measurement accuracy and drift of less than 5% over testing period
- No critical sensor failures during testing period

During boiler down times, sensors were periodically tested with a calibration gas of known concentration. Prior to the real-world deployment at the demonstration site, lab experiments at UTRC were performed to quantify cross sensitivity to other gaseous species.

***Objective 8 – Ensure system availability.*** Availability was to be assessed after the system was installed and commissioned in Watervliet. It should be noted that strategies to ensure continuous operation in face of failure of non-essential system components was to be implemented. Some of those strategies include reverting to less efficient operation or reduced functionality while avoiding boiler lockdown. The following targets were proposed:

- Availability > 95% at full functionality during the system operational time.
- Exclusion of downtime that is due to voluntarily chosen system modifications that improve the experimental setup (e.g. sensor calibration).

Data acquisition system test logs were to be used to assess system operation during tests.

***Objective 9 - Evaluate Years to Payback***. Payback was assessed using NIST's Building Life Cycle cost program. The following targets were proposed:

- < 1 year for the demonstration boiler.

To compute this metric, a typical yearly usage profile of a similar 25 MMBtu/h boiler was used to quantify season long boiler efficiency in objective 1 and system operating cost in objective 6 to obtain payback information. It should be noted that the payback target was set at times where natural gas prices were much higher than those current at time of writing of this report.

## 3.2 QUALITATIVE PERFORMANCE OBJECTIVES

***Objective 1 - Ensure ease of installation and configuration.*** Ease of installation is an important attribute for a boiler control product. The three main aspects are: (1) mechanical installation, in this case mostly the gas sensing package, (2) controls algorithm configuration and (3) visualization/DAQ computer setup. This performance was to be measured by interviews, conducted with system installers operating at the site and other Fireye installers. The success criteria was to collect overall positive feedback and recommendations on system use and setup.

***Objective 2 – Ensure ease of use for boiler operator.*** Ease of use by the boiler operator is required to ensure the system is being used as intended, yielding the expected efficiency gains. For that to happen, operators must understand its working, diagnose faulty behavior and possibly contribute with continued fine tuning of the system. The last aspect must be carried out with special care, as there is a danger to degrade performance unintentionally. Interviews were to be used to assess ease of use of the demonstration technology, involving Watervliet Arsenal boiler plant operators. The success criterion is to obtain positive operator feedback relative to impressions on using of the system.

***Objective 3 – Ensure system maintainability.*** System maintainability is associated with avoiding service calls outside the regular maintenance interval. As the duration of the demonstration was relatively short, only limited data is available. Therefore we planned to rely on expert opinions from operators and installers, predicting the anticipated maintenance schedules during multi-year operation, also based on availability information collected at Objective 8. The success criterion is customer acceptance of the required level of maintenance and willingness to consider installation of it at other sites.

# 4. FACILITY/SITE DESCRIPTION

The main boiler plant at Watervliet Arsenal (WVA), Watervliet, New York was the site of the demonstration of the advanced boiler control technology. Demonstration was carried out on a 30 year old 25 MMBtu/h boiler manufactured by Trane.

The central plant at WVA has 3 large boilers providing steam to the Arsenal for heating and industrial use, and a smaller auxiliary 25 MMBtu/h water-wall boiler which is used during plant startup and in periods of peak demand. This auxiliary boiler is fitted with a Coen Fyr Compact Burner and uses linkage-based positioning of fuel and air opening, which is typical of the boilers (in the <100MMBtu size range) found at DoD sites. Boilers similar in size and age to the one selected for demonstration are in use in many installations across DoD. For example, the Army owns 214 sites with >10 MMBtu/h single burner oil/gas boilers for a total capacity of almost 34,000MMBtu/h, more than 90% of which are older than 10 years.

Figure 30 –The demonstration boiler.

The boiler at WVA is duel fuel capable although it operates primarily on natural gas. Since the auxiliary boiler is not required to be continuously online, it offered the opportunity to perform offline installation and calibrations during the heating season with minimal interference with plant operations. Additionally, the boiler is representative of the class of boilers under consideration for application of the technology within DoD.

Instrumentation enabling performance quantification was installed to continuously monitor/record necessary operational parameters to define overall performance of the system. The ability to acquire detailed boiler performance measurements was a requirement in order to determine system performance under operation as baseline, SoA and demonstration technology. The installation of all sensors and data acquisition hardware was performed by Steam Plant Systems, Joe Firlet as Lead Engineer.

Demonstration and data collection was conducted during the 2010-11 and 2011-12 heating seasons with minimal disruptions to the facility. Data collection relative to baseline and SoA operations could occur 24/7. The boiler plant personnel kindly agreed to make changes to the operating conditions of the boiler to fulfill the requirements of the test plan, greatly facilitating the task of data collection. For demonstration of the $CO/O_2$ trim algorithm, 24/7 data collection was not pursued as the prototype algorithm was largely untested and not UL certified. As collection sessions required frequent switching between operating modes and boiler shutdowns, those had to be performed carefully to avoid inducing unwanted oscillations in the operation of the other boilers. No major event at the boiler plant occurred which would have disrupted data collection, except for the planned summer shutdown.

## 4.1 FACILITY/SITE LOCATION AND OPERATIONS

Waterlviet Arsenal was also selected because of its proximity to UTRC and Fireye home offices. The site was easily accessible by UTRC personnel from East Hartford, CT (2 h drive) and Fireye personnel from Derry, NH (4 h drive). The UTRC/Fireye team needed to be frequently onsite during setup and testing, although personnel at WVA often agreed to support the demonstration activities. The location of WVA is shown by “A” on the map below. UTRC main offices are near Hartford, CT while Fireye offices are near Manchester, NH.

Figure 31 – Location of demonstration site in Watervliet, NY: close to Fireye and UTRC

The demonstration occurred at Watervliet Arsenal’s central boiler plant. The plant supplies steam to the Arsenal between the months of October and May, while it is open for maintenance only during the cooling season. While installation and upgrades could occur during the summer months, testing was strictly limited to the October to May timeframe.

## 4.2 FACILITY/SITE CONDITIONS

The WVA boiler facility and in particular the auxiliary boiler to be used for the demonstration is fully accessible once the WVA point of contact submits a visitor request to security. The facility

is staffed 24/7 and open year-round allowing for efficient installation, modification and troubleshooting. Weather conditions are typical of the US Northeast where boilers see maximum utilization during the October to May heating season.

Severe weather winter conditions during the 2010-2011 heating season did not particularly impact the demonstration timing, mostly because plant personnel could help with performing some of the tests. On the other hand, warm weather greatly impacted the execution of the demonstration. During the 2010-2011 heating season, the boiler plant experienced end of season shutdown one week earlier than planned, limiting the planned collection of SoA data. The 2011-2012 heating season was characterized by unusually warm weather. This limited the possibility to operate the boiler at maximum capacity during many days, because of the reduced demand for steam. Also, switchover to oil did not occur for similar reasons (the gas utility imposes the Arsenal to switch to oil in situations of very high natural gas overall demand). For this reason, collected data was limited relative to that acquired at low capacity operating points.

In general, the impact on having limited data which do not span the entire firing range, or smaller size sampling at high fire conditions reduces the level of confidence of performance assessment at those operating points. On the other hand, filling the gap by acquiring additional data at the Watervliet boiler site would have required a project extension to the full 2012-2013 heating season and hoping for cold enough weather conditions to allow operation when the steam demand is high enough to enable full load operation. Executing characterization of efficiency performance of a boiler in the field carries the risk of incomplete data. Such risk is associated with variability of weather patterns, demand, availability, and operational constraints which are much higher if compared to demonstrations conducted in laboratory.

# 5. TEST DESIGN

## 5.1 CONCEPTUAL TEST DESIGN

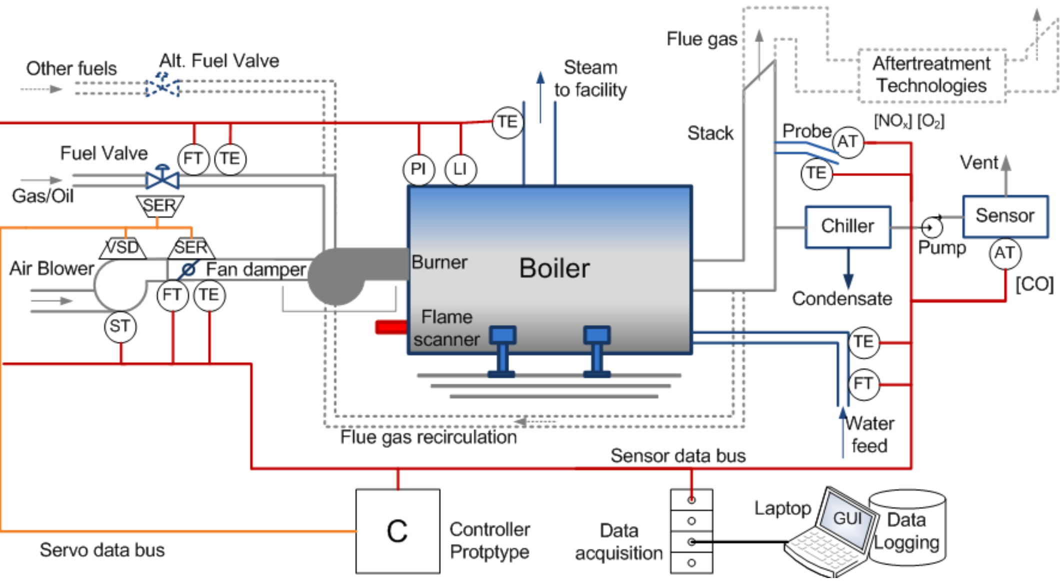



Figure 32 – The proposed demonstration setup, largely implemented as originally planned.

A depiction of the demonstration site and experimental setup can be found in Figure 32. The existing boiler control and monitoring setup was modified incrementally in three phases. In Phase I instrumentation and a data acquisition system was installed to baseline system performance. Phase II included the installation of the State of the Art controller to quantify benefits of switching to that technology. Finally, in Phase III the controller software was updated together with the installation of the “Fireye box” and benefits of for the proposed technology were quantified.

*Phase I: Setup for boiler monitoring and baseline with legacy control (February 2010)*

- The boiler was instrumented with a sufficient set of metering devices to measure airside and waterside properties such as airside inlet and outlet temperatures (TE in Figure 32), water side flow rate (FT) and inlet temperatures, to allow the precise quantification of boiler efficiency (both combustion efficiency and fuel to steam efficiency). Direct measurement of sufficiently accurate air flow measurements turned out to be impractical.
- Flue gas composition was measured (AT) including oxygen, $NO_x$, and CO to monitor combustion characteristics as well as emissions. Laboratory grade instruments or other suitable instrumentation was used for gas species measurements as part of the boiler monitoring system. Measurements redundancies were created to ensure accuracy and verification of performance of different technologies.
- Boiler process variables i.e., water/steam pressure (P) were also measured.
- An all-bus communication network like that specified in Figure 32 was pursued by interconnecting sensors via a number of MODBUS-based networks. However, some sensors were connected via traditional analog input to a data acquisition device. In turns, the data collection unit was connected to a laptop where data logging and monitoring via the

WebCTRL GUI occurred. Backup of data occurred automatically via standard backup system.

*Phase II: Setup for tests with State of the Art control (October 2011)*

- The demonstration setup was upgraded with the Fireye PPC4000 (UL listed) control system (C). The controller was connected to the data collection unit via MODBUS.
- The controller was connected to an existing or a Fireye flame safeguard system through a safety chain connection to ensure safe boiler shutdown in case of flameout or out-of-bound variables. This is part of the current PPC4000 product offering.
- The fuel inlet valves (NG and oil) and air damper were actuated by new Fireye servomechanisms (SER), connected to the controller via data bus with MODBUS protocol.
- At the beginning of Phase II, some of the sensors were repositioned (the steam flow meter and the inlet temperature sensor) to improve the quality of measurements. Old measures were corrected based on new measurements to ensure consistency.

*Phase III: Setup for demonstration of proposed technology (Jan 2012)*

- Upgrade of the demonstration setup was limited to uploading the new controller software on the PPC4000 system and installation of the new sensor box (the "Fireye" box) to enable reading CO measurements and execute the $CO/O_2$ trim control algorithm.

During the three phases of demonstration, the boiler was operated either in commissioning mode or in controlled mode. Automatic startup and shutdown procedures were executed anytime the boiler was brought online or offline. Standard procedures did not change in the three phases of the demonstration.

### 5.1.1 Instrumentation and Monitoring

A data acquisition system using digitization and control hardware from Automated Logic Corporation (ALC) was installed prior to baseline testing. This system consisted of an Automated Logic ME812u-LGR (with 200 Modbus integration points), two MEX816u controllers, and WebCTRL 500 software (Figure 33). All sensors were interfaced through the ALC system and recorded on a laptop in the boiler control room. The GUI described in Section 2.2.3 enabled real-time monitoring of the boiler performance and data download either from viewing the laptop or remotely via a 3G link and GoToMyPC software.

Figure 33 – The ALC data acquisition boards for analog and MODBUS signals.

The sensors shown in Table 4 were installed at the beginning of the demonstration prior to testing of the baseline configuration. Stack gas species were monitored with laboratory grade instruments while sensor development and packaging was ongoing. Later, new sensors were added for the SoA, "legacy", and advanced technology demonstrations.

Table 4 – Data signals recorded prior to testing of the Baseline configuration

| # | Point Name | Type | Instrument Range | Vendor / Model | process variables | Trend Interval |
|---|---|---|---|---|---|---|
| 1 | Temperature Air | RTD | 0 to150 F | Fireye NEX-1002 | ambient temperature | 1 sec |
| 2 | Temperature Water | RTD | 0 to 300 F | | feedwater temperature | 1 sec |
| 3 | Temperature Stack | RTD | 0 to 500 F | Fireye NEX-1002 | exhaust gas temperature | 1 sec |
| 4 | O2 | Zirconia | 0 to 20.90% | Fireye NEX-1002 | exhaust oxygen concentration | 1 sec |
| 5 | Pressure Steam Supply | pressure | 0-300 psig | Foxboro smart tranmitter | delivery steam pressure | 1 sec |
| 6 | Mass flow rate Gas | thermal | 0 - 96,000 SCFH | Fox FT2 | gas mass flow and temperature | 1 sec |
| 7 | Mass flow rate Oil | vortex | 0 to 5 gallons/min | Rosemount | oil mass flow and temperature | 1 sec |
| 8 | Mass flow rate Water | vortex | 0 to 30,000 lbm/hr | Foxboro | feedwater flowrate | 1 sec |
| 9 | Mass flow rate Steam | vortex | 0 to 30,000 lbm/hr | Sierra Innova 240 | steam mass flow, vol flow, T, P | 1 sec |
| 10 | CO | NDIR | 0 to 500 ppm | Siemens UltraMet 22 | exhaust carbon monoxide concentration | 1 sec |
| 11 | O2 | paramagnetic | 0 to 10 % | Beckman 755 | exhaust oxygen concentration | 1 sec |
| 12 | CO2 | NDIR | 0 to 20,000 ppm | Siemens UltraMet 22 | exhaust carbon dioxide concentration | 1 sec |
| 13 | NOx | Chemiluminescent | 0 to100 ppm | ThermoElectron M35G | exhaust NO + NO2 concentration | 1 sec |
| 14 | NO | Chemiluminescent | 1 to100 ppm | ThermoElectron M35G | exhaust nitric oxide concentration | 1 sec |
| 15 | NO2 | Chemiluminescent | 2 to100 ppm | ThermoElectron M35G | exhaust nitrogen dioxide concentration | 1 sec |
| 16 | dP stack | pressure | 0 to 100 Pa | | pressure difference | 1 sec |

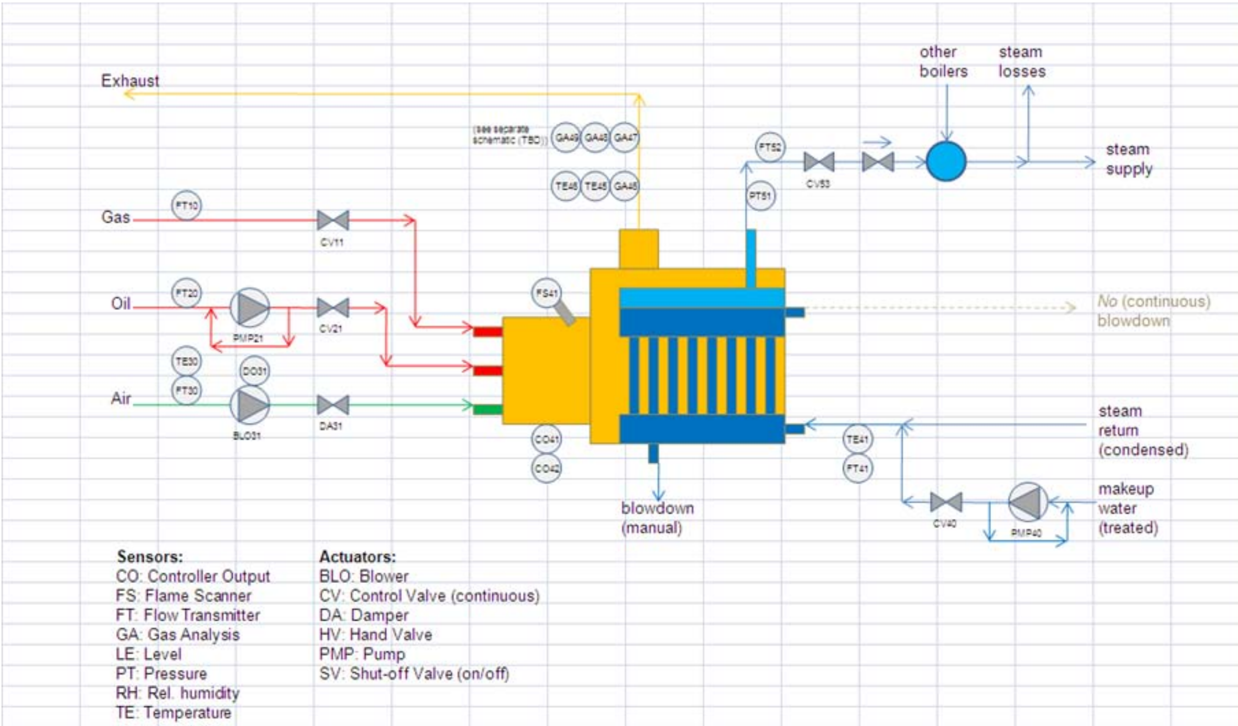



Figure 34 – The process and instrumentation diagram for the boiler in baseline state

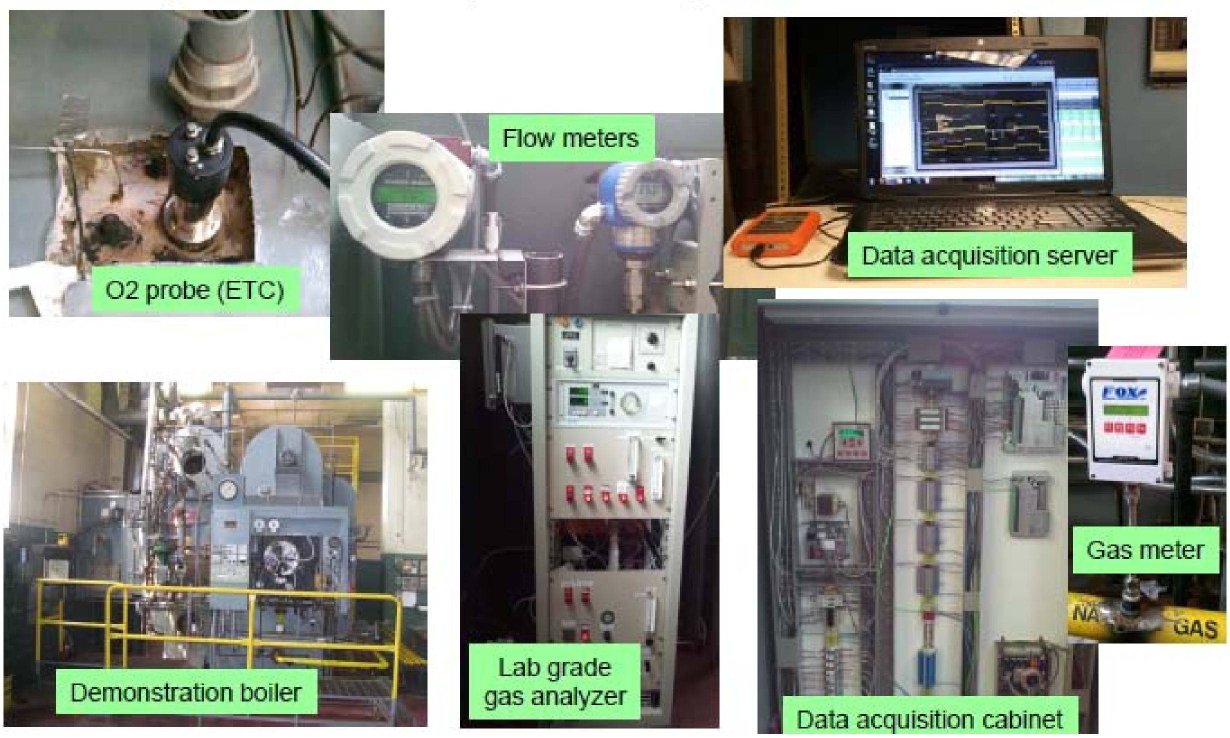



Figure 35 – Sensors and data acquisition overview. The boiler has not been upgraded.

### 5.1.2 Controls

Boiler steam pressure was generally controlled at a fixed set point to meet steam plant requirements. Usually, another boiler of the plant was tasked with keeping system pressure constant. The boiler was seldom operated in modulation mode to control pressure. In that case, the pressure controller adjusts the firing rate command which provides the necessary firing power to maintain the desired pressure. The pressure controller typically compensates for pressure variations induced by changes in steam demand. The boiler is also equipped with level controls to ensure an adequate supply of water to the drums. Blowdown is performed manually on a daily basis for cleanup purposes.

As explained in Section 2, combustion control was made available to set the ratio of fuel and air flow needed for combustion. The PPC4000 system installed for demonstration provided both combustion control as well as process pressure control capabilities.

## 5.2 BASELINE CHARACTERIZATION

Baseline characterization of performance objectives was carried out by operating the boiler with existing linkage based controls. Data was collected to evaluate baseline performance under a number of distinct characterization scenarios.

**Boiler operation characterization across the firing range**. The boiler was operated at fixed, predefined firing rates or operating points for a predefined period of time (at least 2 hours inclusive of system transient and settling). The following operating points were selected: ('Low Fire', 25%, 50%, 75% and 'High Fire'). Transition between operating points occurred as a step change of the firing rate signal that govern the fuel/air linkage. The following variables were *not* going to be changed but were be monitored to characterize conditions variability: fuel composition (available daily from the local utility), sensor drift or failure, boiler room temperature, boiler room relative humidity, condensate return flow and temperature. The test was repeated several times to ensure sampling with an adequate level of confidence.

**Boiler characterization during regular operation**. Extended operation tests were conducted to monitor the boiler operation across an extended period of time of more than 24 hours. Measurements were collected for performance characterization as illustrated for firing range characterization tests, but also to determine the effect of slow, exogenous variations.

**Commissioning**. Baseline data on commissioning time for the linkage-based system was collected by performing a re-tuning session by Joe Firlet of Steam Plant Systems. Time to set the fuel-air linkage system across the firing range was assessed. It should be noted that what was performed was a fine tuning of an already installed device. This did not enable the evaluation of duration of first time commissioning.

Since the Watervliet Arsenal site almost exclusively runs on natural gas, experiment repeats were be done using that fuel. A smaller set of experiments were performed using No. 2 oil. Performance evaluation with natural gas is most relevant, as the majority of DoD boilers (circa 80%) utilize that fuel, sometimes with backup oil operation to take advantage of interruptible rates and supply disruptions. Yet, there are still 20% of boilers which only use oil, so that performance characterization for that fuel is relevant. The use of oil for heating will decline over time because of boiler conversion programs. We believe that while such conversion occurs, the

application of combustion control technology to existing boiler is an investment that will allow immediate energy savings in the meantime. Last but not least, the adoption and diffusion of liquid biofuels will present efficiency improvement potential similar to those observed with oil.

A description of baseline experiments is available in Section 5.4 as part of the operational testing activities. In addition to baseline characterization ad-hoc testing, information on past year boiler performance was obtained by the boiler plant personnel at Watervliet Arsenal, who have recorded the plant boiler's operation on a daily basis on paper records. Information relative to steam output (based on a pre-existing steam flow meter) and stack oxygen concentrations were recorded. Of particular interest are historical daily averages of $O_2$ stack concentrations, as this measure is directly related to combustion efficiency. Data between 2007 and 2011, before the demonstration started, are reported in the figure below. Measurements were taken with a legacy Rosemount sensor. The chart on the top shows all data between the 2007-08 and 2010-11 heating seasons, that on bottom the evolution of concentrations in the days preceding the start of the demonstration. The cause of sudden drop of $O_2$ concentration is associated with re-tuning of the linkage system that was performed prior to start on the testing sessions.

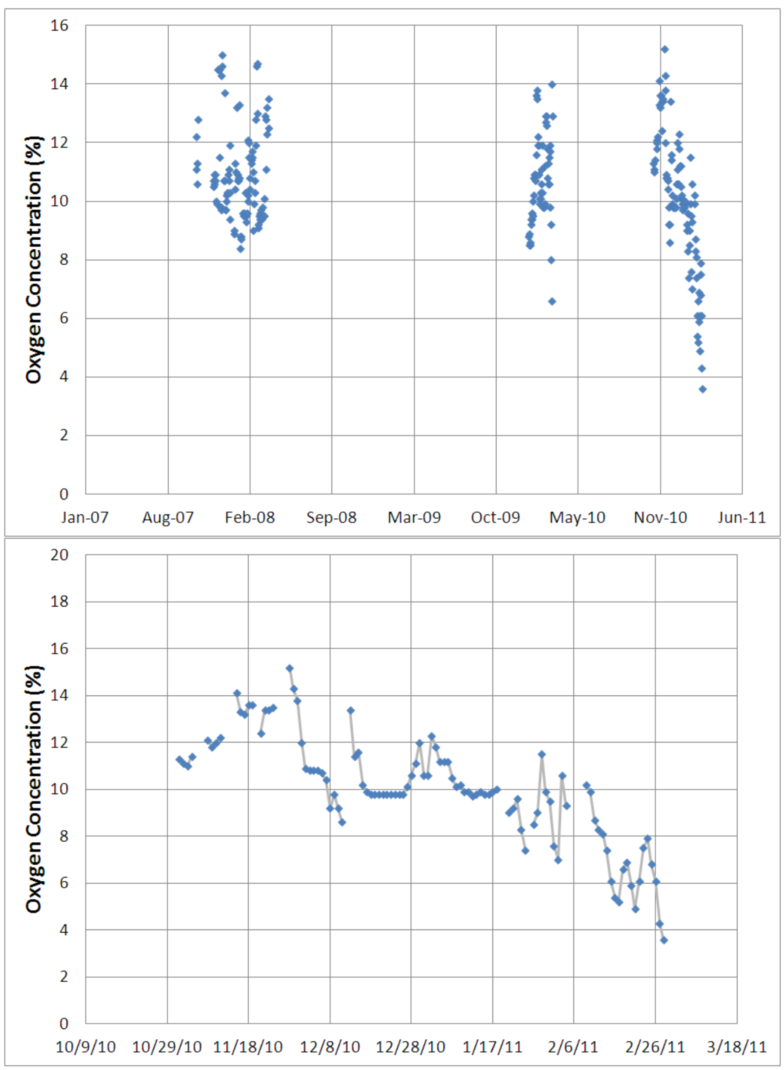


Figure 36 – Historical daily average O2 concentrations measured at the stack

Pictures showing the baseline linkage-based control are reported below. The presence of crank shafts and mechanical interconnections are clearly visible.

Figure 37 – Mechanical linkages constitute the legacy control solution.

## 5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The demonstrated new technology makes use of standard components that are part of the PPC4000 efficiency control system and builds advanced functionality by modifying some of them. The overall architecture and safety features do not change compared to the State of the Art solution. Technology components are described as follows.

- *Servomechanisms*: Fireye servomechanisms act on the air damper and the gas and oil supply valves to modulate the inlet of fuel and air. The servomechanisms are installed on the air and fuel lines to directly drive dampers and valves in lieu of the original linkage system. Communication to and from the controls is over MODBUS.

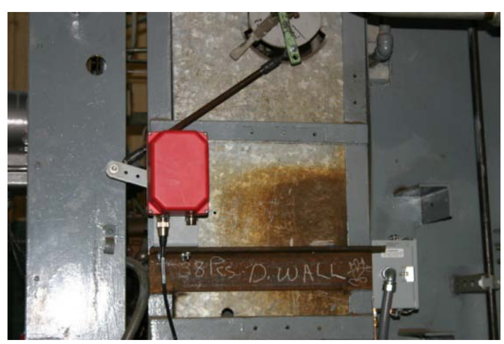


Figure 38 –Fuel/air positioning actuators come in different sizes, depending on their torque requirements.  Fuel servomotor on left, air servomotor on right.

- *Flame scanner*: utilizing infrared (IR), ultraviolet (UV) or a combination of the two. A scanner monitors the flame, interrupting fuel supply in case of unexpected extinction. The

flame scanner is installed on the boiler in proximity of the burner to have line of sight on the flame. The existing scanner will be connected to the combustion control system.

Figure 39 –Flame scanners verify the existence of a flame at the burner. They are interlocked with the fuel supply, representing an important safety component for every boiler.

- *Boiler control system box*: contains flame safeguard system, process variable controller, combustion controller (with new algorithm embedded), and user interface display. Control devices are interconnected via electrical and bus lines and housed in a suitable enclosure. The enclosure is installed near the boiler and interconnected to the servomotors, the scanner and the data acquisition system.

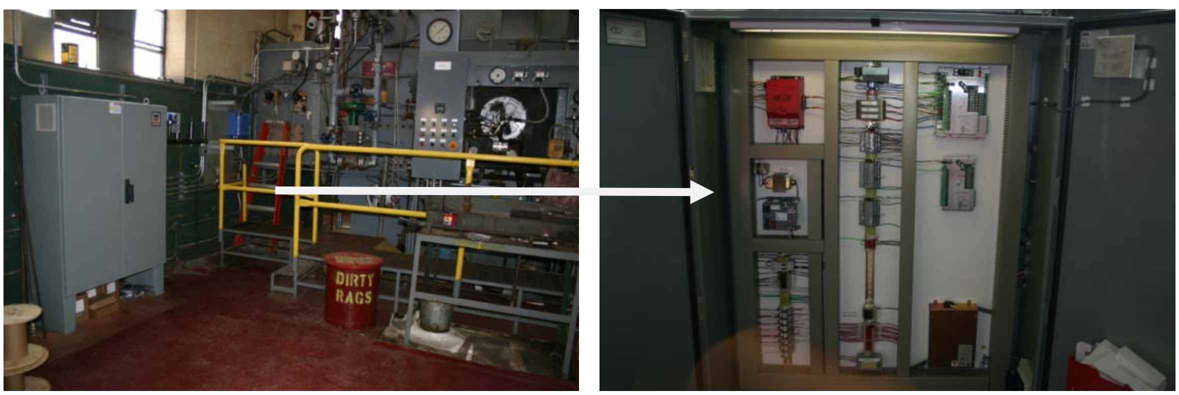



Figure 40 – The boiler control system is located in an enclosure near the boiler.

- *Gas sampling probe for SoA operation*: state-of-the-art systems at Fireye include an oxygen sensor that samples the exhaust composition 'in situ'. The probe is inserted in the boiler stack and is connected to the sensor box via a data line. Two Fireye $O_2$ probes are shown below as installed on the exhaust stack of the Watervliet boiler. One of them (left) was used for closed loop operation in SoA mode.

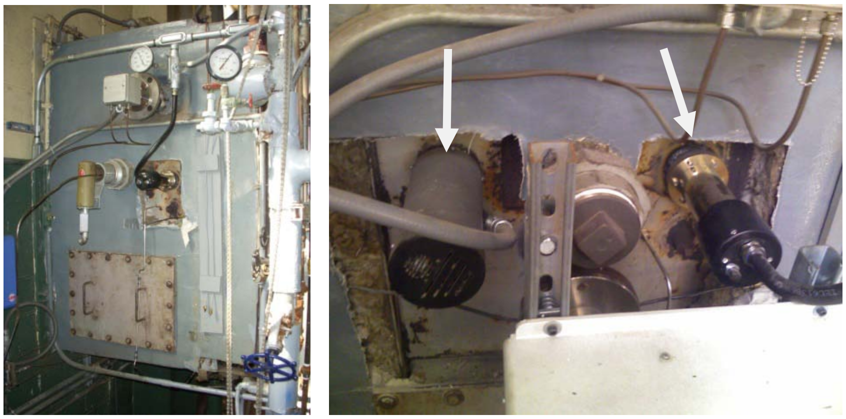


Figure 41 – Matured by automotive applications, zirconium oxide solid state oxygen sensors are well-established technology

- *Gas sampling probe for CO/O2 trim operation*: Electrochemical sensors for CO are readily available at an affordable price[1]. Gas sensors are packaged in the "Fireye" sensor box together with devices to condition the gas sample (via cooling and drying).

Figure 42 – The prototype multi-sensor box used for CO/O2 trim closed loop control

- *Gas Analysis subsystem*: suitable sensors for continuous monitoring of chemical species such as CO and $NO_x$ were packaged in a sensor box. The sensor box ("Forney" box) was installed in proximity of the probe close to the stack, to minimize transport time of the gas sample.

[1] http://www.alphasense.com; http://www.figarosensor.com; http://www.membrapor.ch


Figure 43 – The Fireye and Forney box installed in proximity of each other and near the stack.

## 5.4 OPERATIONAL TESTING

Demonstration activities occurred between February 2011 and April 2011, resumed in October 2011, and were completed in March 2012. The following testing activities were conducted:

0. Instrumentation and data acquisition system installation (December 2010 to January 2011);
1. Baseline characterization with linkage control (February 2011 to March 2011);
2. SoA characterization with PPC4000, O2 trim mode (March 2011 to April 2012);
3. SoA characterization with PPC4000, O2 trim mode (October 2011 to December 2011), with repositioned instrumentation;
4. "Legacy" characterization with PPC4000, open loop parallel positioning mode calibrated to match boiler historical data (November 2011);
5. CO/O2 trim characterization (February 2012 to March 2012).
6. Decommissioning (March 2012 to April 2012)

Transition from activity (2) to activity (3) was necessary as initial positioning of the air inlet temperature sensor and the steam flow sensor were considered incorrect. As the inlet air temperature sensor was installed too close to the boiler, it would give excessively high readings associated with the boiler wall proximity. The steam flow meter was interfering with the older meter preexisting the demonstration and needed to be repositioned away from it. Additionally, the stack temperature thermocouple was recalibrated to enable reading of temperatures higher than 500°F, since the boiler exhaust occasionally exceeded the upper limit of that original range.

Activity (4) was not originally planned as part of the demonstration, but was deemed necessary to measure boiler performance associated with the operation observed during the previous years' heating seasons as illustrated in Figure 36. Necessity of this step arose from the finding that before activity (1) the boiler was re-tuned to operate at lower $O_2$ concentrations by plant maintenance personnel. It was therefore decided to collect data both associated with the re-tuned linkage and with operation reflective of legacy pre-demonstration oxygen levels.

### 5.4.1 Baseline Tests

The following activities preceded baseline data collection:

1. Mechanical and plumbing work for sensor installation;
2. Electrical work for wiring;
3. Installation of control and data acquisition boxes;
4. Configuration and commissioning of the data acquisition system;
5. Calibration of sensors.

As mentioned above, a calibration of the linkage control was performed prior to the demonstration start. During the execution of baseline data collection no particular preparation to tests was conducted except for periodic calibration of gas sensors. Calibration occurred on a periodic basis and not for all demonstration sessions. The operation of the boiler is reported in the table below. Firing rate was changed at different levels to capture system performance. For each test, the date, time of firing rate setting, and fuel used is reported.

Table 5 – Baseline data gathering, sequence of operations.

| Date | time | time stop | Firing rate gas | Firing rate oil |
|---|---|---|---|---|
| 18-Feb | 0:30 | 7:35 | 5 | |
| | 7:35 | 11:10 | 20 | |
| | 11:10 | 1:00 | 10 | |
| 19-Feb | 7:15 | 9:20 | 25 | |
| | 9:20 | 11:45 | 50 | |
| | 11:45 | 1:00 | 15 | |
| 20-Feb | 7:20 | 9:15 | 100 | |
| | 9:15 | 11:00 | 75 | |
| | 11:00 | 13:00 | 50 | |
| | 13:00 | 15:00 | 25 | |
| 21-Feb | 7:45 | 9:42 | 100 | |
| | 9:42 | 11:45 | 75 | |
| | 11:45 | 13:55 | 50 | |
| | 13:55 | 16:00 | 25 | |
| 22-Feb | 7:00 | 8:10 | 29 | |
| | 8:10 | 9:14 | 100 | |
| | 9:14 | 10:50 | | 100 |
| | 10:50 | 12:25 | | 75 |

| Date | time | time stop | Firing rate gas | Firing rate oil |
|---|---|---|---|---|
| | 12:25 | 14:05 | | 50 |
| | 14:05 | 16:00 | | 25 |
| 23-Feb | 8:20 | 9:00 | | 30 |
| | 9:00 | 10:08 | | 100 |
| | 10:08 | 13:15 | | 75 |
| | 13:15 | 15:05 | | 50 |
| | 15:05 | 17:00 | | 25 |
| 26-Feb | 0:00 | 1:47 | 50 | |
| | 1:47 | 4:04 | 75 | |
| | 4:04 | 5:40 | 100 | |
| | 5:40 | 23:35 | 25 | |
| | 23:35 | 2:00 | 50 | |
| 27-Feb | 2:00 | 4:05 | 75 | |
| | 4:05 | 5:40 | 100 | |
| | 5:40 | 16:15 | 25 | |
| | 16:15 | 23:25 | 15 | |
| | 23:25 | 1:45 | 50 | |
| 28-Feb | 1:45 | 4:08 | 75 | |
| | 4:08 | 5:40 | 100 | |
| | 5:40 | 23:00 | 25 | |
| | 23:00 | 23:40 | 15 | |
| | 23:40 | 1:50 | 50 | |
| 1-Mar | 1:50 | 4:05 | 75 | |
| | 4:05 | 5:40 | 100 | |
| | 5:40 | 23:40 | 25 | |
| | 23:40 | 1:53 | 50 | |
| 2-Mar | 1:53 | 4:15 | 75 | |
| | 4:15 | 6:00 | 100 | |
| | 6:00 | 23:55 | 25 | |
| | 23:55 | 1:50 | 50 | |
| 3-Mar | 1:50 | 4:10 | 75 | |
| | 4:10 | 5:45 | 100 | |
| | 5:45 | 6:10 | 25 | |
| | 6:10 | 10:40 | 40 | |
| | 10:40 | 12:50 | 25 | |
| | 12:50 | 7:45 | 15 | |
| 4-Mar | 7:45 | 7:45 | 30 | |
| 5-Mar | 0:00 | 0:00 | 25 | |
| 6-Mar | 0:00 | 14:35 | 25 | |
| | 14:35 | 19:00 | 20 | |
| | 19:00 | 20:10 | 25 | |
| 7-Mar | 20:10 | 0:00 | 25 | |

| Date | time | time stop | Firing rate gas | Firing rate oil |
|---|---|---|---|---|
| 8-Mar | 0:00 | 2:45 | 25 | |
| | 2:45 | 3:25 | 40 | |
| | 3:25 | 5:15 | 50 | |
| | 5:15 | 12:55 | 40 | |
| | 12:55 | 13:35 | 75 | |
| | 13:35 | 14:45 | 85 | |
| | 14:45 | 16:10 | 100 | |
| | 16:10 | 17:00 | 50 | |
| 9-Mar | 15:45 | 17:25 | 15 | |
| | 17:25 | 19:07 | 25 | |
| | 19:07 | 20:40 | 50 | |
| | 20:40 | 22:08 | 75 | |
| | 22:08 | 8:00 | 25 | |
| 10-Mar | 8:00 | 12:15 | 25 | |
| | 12:15 | 14:45 | 50 | |
| | 14:45 | 15:15 | 75 | |
| | 15:15 | 17:40 | 25 | |
| | 17:40 | 19:20 | 50 | |
| | 19:20 | 0:00 | 15 | |
| 13-Mar | 0:00 | 15:30 | 15 | |
| | 15:30 | 18:00 | 25 | |
| | 18:00 | 19:30 | 50 | |
| | 19:30 | 20:11 | 75 | |
| | 20:11 | 22:00 | 50 | |
| | 22:00 | 0:00 | 15 | |
| 14-Mar | 8:00 | 11:15 | 30 | |
| | 11:15 | 11:45 | 40 | |
| | 11:45 | 23:45 | 50 | |
| 15-Mar | 8:00 | 16:00 | 50 | |
| | 16:00 | 0:00 | 25 | |
| 16-Mar | 0:00 | 0:00 | 25 | |
| 17-Mar | 0:00 | 9:00 | 25 | |
| | 9:00 | 11:35 | 15 | |
| | 11:35 | 17:00 | 25 | |
| 18-Mar | 0:00 | 0:00 | 25 | |
| 19-Mar | 8:00 | 12:00 | 25 | |
| | 12:00 | 12:30 | 50 | |
| | 12:30 | 14:30 | 75 | |
| | 14:30 | 16:30 | 50 | |
| | 16:30 | 20:00 | 25 | |
| 20-Mar | 8:00 | 12:00 | 25 | |
| | 12:00 | 13:30 | 75 | |

| Date | time | time stop | Firing rate gas | Firing rate oil |
|---|---|---|---|---|
| | 13:30 | 14:45 | 85 | |
| | 14:45 | 0:00 | 50 | |
| 21-Mar | 8:00 | 14:00 | 50 | |
| | 14:00 | 15:30 | 100 | |
| | 15:30 | 0:00 | 25 | |
| 22-Mar | 0:00 | 6:00 | 25 | |
| | 6:00 | 6:30 | 85 | |
| | 6:30 | 8:30 | 100 | |
| | 8:30 | 10:00 | 85 | |
| | 10:00 | 12:00 | 70 | |
| | 12:00 | 13:00 | 60 | |
| | 13:00 | 14:00 | 50 | |
| | 14:00 | 15:00 | 40 | |
| 23-Mar | 8:00 | 10:00 | 40 | |
| | 10:00 | 12:00 | 50 | |
| 25-Mar | 0:00 | 10:00 | 25 | |
| | 10:00 | 12:30 | 15 | |
| | 12:30 | 13:30 | 50 | |
| | 13:30 | 19:00 | 25 | |

During the execution of the test sequence, recalibrations and adjustments to the data acquisition system occurred. Availability of sufficient data was ensured by the large numbers of test repetitions. Operability of the boiler largely depended on steam demand which had an impact on the maximum firing rate at which data could be collected on a given day.

### 5.4.2 SoA Characterization – March/April Tests

The installation and commissioning of the PPC4000 system occurred prior to starting SoA characterization testing. The controller replaced the original linkage system. In addition, all operational variables available from the controller via MODBUS (including operation mode, firing rate, and servomechanism position) were acquired by the data acquisition system.

Prior to testing, commissioning and parameter setting was performed on the PPC4000 controller. Tuning included the setting of predefined servomechanisms position across the firing range and setting of the $O_2$ concentration targets that the O2 trim controller operates at. The following table illustrates the commissioning points that were set. Specifically, the commissioning process involves the development of an air to fuel profile which was used to transition the boiler from a standby state (low fire) to maximum firing rate (high fire). During this process the installer establishes key parameters to maintain boiler performance throughout testing.

Table 6 – Commissioning table for SoA control operation.

| Points | Air servo | Gas servo | O2% |
|---|---|---|---|
| P03 | 5.2 | 9.3 | 10.2 |
| P04 | 8.3 | 11.2 | 9.1 |
| P05 | 12.0 | 13.5 | 7.4 |
| P06 | 16.0 | 15.0 | 6.8 |
| P07 | 20.1 | 16.5 | 6.1 |
| P08 | 27.0 | 18.8 | 4.5 |
| P09 | 31.0 | 19.7 | 4.2 |
| P10 | 36.0 | 21.0 | 3.5 |
| P11 | 42.3 | 22.5 | 2.6 |
| P12 | 50.1 | 24.0 | 2.2 |
| P13 | 62.0 | 25.9 | 1.9 |
| P14 | 73. | 26.9 | 1.8 |

In addition, other parameters of the controller were set, including the gains for the O2 trim proportional integral (PI) control, a transport delay setting, limits to the trim signal to ensure safe operation of the boiler. The parameters mentioned above ensure safe operation of the system but do not affect efficiency performance.

Before testing, a functional check of the data acquisition system was executed. This included verification of data recording and daily report generation. Each data point was verified to ensure that the data being recorded in a specific field correspond to physical instrument. To ensure accurate recording of gas species a sample gas (certified) supplied to each instrument, then the visual output was checked to ensure that it displayed the correct concentration of the gas. Verification of all analog signals was done by configuring the DAQ to interpret the 4-20mA signal and correlate the signal to a calibrated scale/ range for each unit. Data associated with the PPC4000 operation was captured by using the MODBUS location of each parameter. Further verification was done to ensure that the DAQ signal matched the PPC4000 display output.

*Test operation strategies/constraints*

The demonstration boiler is not a standalone unit; this unit is connected to common steam pipe line with the other boilers. Plant pressure is controlled by a Master boiler. The demonstration efficiency controller is independent on the other boilers' control, including the master. However, interactions among boilers can occur through the steam line, so that careful action has to be taken during testing to avoid unwanted plant dynamics. To this purposes, the following guidelines were rigorously adopted:

1. Steam pressure was maintained at 135 Psi at the boiler master.
    a. Transition between firing rates was performed slowly so avoid pressure swings by allowing the boiler master to adapt and maintain pressure constant.
2. At NO time the steam production from the demonstration boiler could be the only source of steam. Another boiler had to be in operation.
    a. Total load capacity requested was confirmed with the boiler operator.
        i. Minimum acceptable load capacity for the other boilers was discussed with the operator to determine the maximum allowable output of the demonstration boiler on a given day.

*Boiler Startup Procedure*

A standard procedure for startup and shutdown was followed each time a transition among boiler operation modes was necessary. This was not necessarily performed at start of each test sequence, but rather when it was necessary to make adjustments to the PPC4000 controller. All of the following steps were performed at first startup:

1. Turn on data acquisition PC (was left on 24/7)
2. Turn on gas analysis instrument (was left on 24/7)
    a. "Forney box" (multi-sensor)
    b. Lab grade instrumentation rack
3. Verify that PPC4000 is powered (was left on 24/7)
4. Open gas fuel supply to boiler plant
5. Ensure that the water level within boiler is sufficient for start-up
6. Set the following switch on PPC4000 boiler controller as follow
    a. Fan to AUTO
    b. Fuel to Gas
    c. Boiler switch to ON.
7. On the PPC4000 controller panel perform the following:
    a. Press the home key
        i. Unit should be in the standby mode
    b. Set unit to manual by pressing the Auto/Manual key
        i. A led light will appear when in manual mode
    c. Press the low fire key to select low fire
8. Press boiler on key on key pad
    a. Boiler should go through all purge phase and start up to low fire
    b. Ensure Boiler Master within boiler room reaches 135 PSI

*Boiler Shutdown Procedure:*

Whenever required, including at transition between fuels, the following shutdown procedure had to be followed:

1. Reduce boiler firing rate to the "low fire" position
    a. This was slowly completed while maintaining steam pressure at 135 pi
       135psi is the required steam pressure at the Arsenal
    b. Hold at low fire for 3-5 min.
       Verify pressure is stable at 135psi
2. Press boiler on/off button
3. Set the following switch on boiler controller as follow
    a. Fan to OFF
    b. Boiler switch to OFF
4. Manually close the following valves
    a. Gas fuel valve
    b. Water supply valve

Tests for acquisition of data and their duration are reported in the table below. All tests were performed with natural gas:

Table 7 – SoA data gathering, Spring 2011.

| Date | Time | Firing rate (0-100) (gas) |
|---|---|---|
| 14-Apr | 3hr 13min | 80 |
| | 7hr 15min | 25 |
| | | |
| 15-Apr | 7hr 2min | 30 |
| | 42min | 35 |
| | 1hr 15min | 100 |
| | 2hr 30min | 80 |
| | 6hr 48min | 50 |
| | | |
| 16-Apr | 7hr 47min | 50 |
| | 10hr 50min | 25 |
| | | |
| 17-Apr | 24hr | 25 |
| | | |
| 18-Apr | 9hr 30min | 25 |
| | 10hr 42min | 50 |
| | | |
| 19-Apr | 7hr 15min | 50 |
| | 1hr 13min | 100 |
| | 1hr 45min | 80 |
| | 12hr 7min | 50 |
| | | |
| 20-Apr | 24hr | 50 |
| 21-Apr | 24hr | 50 |
| 22-Apr | 23hr 27min | 50 |
| 23-Apr | 2hr 15min | 80 |
| | 3hr 42min | 50 |
| | 3hr 20min | 90 |
| | 11hr 30min | 30 |
| 24-Apr | 1hr 7min | 60 |
| | 2hr 40min | 40 |
| | 19hr 50min | 30 |
| 25-Apr | 1hr 3min | 75 |
| | 2hr 8min | 45 |
| | 19hr 15min | 30 |
| 26-Apr | 1hr 37min | 75 |
| | 3hr 42min | 45 |

| Date | Time | Firing rate (0-100) (gas) |
|---|---|---|
| | 1hr 55min | 30 |
| | 15hr 48min | 25 |
| 27-Apr | 1hr 45min | 45 |
| | 8hr 18min | 30 |
| | 11hr | 30 |

### 5.4.3 SoA Characterization – October to December Tests

During the boiler summer shutdown, repositioning and reconfiguration of sensors occurred as illustrated above. Repositioning of the inlet air temperature and steam flow sensors was executed to improve data reliability. List of tests executed is reported in the table below.

Table 8 – SoA natural gas data gathering, fall 2011.

| **Date** | Duration | Firing Rate % |
|---|---|---|
| **29-Oct** | 2 h 2 min | 100 |
| | 1 h 57min | 85 |
| | 1 h 57min | 70 |
| | 9 h 45 min | 40 |
| **30-Oct** | 24 h | 40 |
| **31-Oct** | 7 h 55 min | 40 |
| | 1 h 58 min | 70 |
| | 1 h 50 min | 90 |
| | 1 h 15 min | 40 |
| | 27 min | 100 |
| | 9 h 5 min | 40 |
| **3-Nov** | 23 h 57 min | 40 |
| **4-Nov** | 15 h 10 min | 40 |
| | 5 h 47 min | 35 |
| **5-Nov** | 23 h 20 min | 35 |
| **6-Nov** | 23 h 22 min | 40 |
| **11-Nov** | 23 h 57 min | 25 |
| **12-Nov** | 23 h 57 min | 25 |
| **13-Nov** | 23 h 57 min | 25 |
| **15-Nov** | 7 h 42 min | 25 |
| | 2 h | 50 |
| | 3 h 58 min | 40 |
| | 5 h 23 min | 40 |
| **16-Nov** | 22 h 35 min | 20 |
| **17-Nov** | 22 h 45 min | 20 |
| **18-Nov** | 8 h 47 min | 20 |
| | 1 h 58 min | 70 |

| Date | Duration | Firing Rate % |
|---|---|---|
| | 1 h 55 min | 90 |
| | 2 h | 100 |
| | 1 h 55 min | 70 |
| **19-Nov** | 3 h 43 min | 50 |
| | 6 h 55 min | 40 |
| | 12 h 40 min | 30 |
| **20-Nov** | 23 h 57 min | 30 |
| **21-Nov** | 23 h 57 min | 30 |
| **22-Nov** | 23 h 57 min | 30 |
| **23-Nov** | 23 h 57 min | 30 |
| **24-Nov** | 7 h 35 min | 30 |
| | 1 h 45 min | 100 |
| | 1 h 43 min | 90 |
| | 1 h 52 min | 70 |
| | 9 h 45 min | 30 |
| **25-Nov** | 23 h 57 min | 30 |
| **26-Nov** | 23 h 57 min | 30 |
| **27-Nov** | 23 h 57 min | 30 |
| **6-Dec** | 3 h 57 min | 70 |
| | 19 h 37 min | 30 |
| **7-Dec** | 23 h 40 min | 30 |
| **8-Dec** | 4 h | 90 |
| | 5 h 30 min | 30 |
| | 1 h 32 min | 70 |
| | 2 h | 60 |
| | 5 h 28 min | 30 |
| **9-Dec** | 7 h 32 min | 30 |
| | 40 min | 40 |
| | 2 h 25 min | 70 |
| | 45 min | 50 |
| | 2 h 45 min | 30 |
| | 3 h 52 min | 70 |
| | 1 h 47 min | 30 |
| **10-Dec** | 7 h 22 min | 30 |
| | 2 h 40 min | 70 |
| | 11 h 12 min | 40 |
| **11-Dec** | 3 h 32 min | 90 |
| | 2 h 58 min | 35 |
| | 3 h 8 min | 70 |
| | 1 h 35 min | 50 |

| Date | Duration | Firing Rate % |
|---|---|---|
| | 3 h 47 min | 100 |
| | 3 h 25 min | 40 |
| **12-Dec** | 3 h 22 min | 90 |
| | 3 h 18 min | 35 |
| | 3 h 40 min | 70 |
| | 1 h 25 min | 50 |
| | 3 h 52 min | 100 |
| | 3 h 42 min | 70 |
| **13-Dec** | 3 h 47 min | 90 |
| | 3 h 10 min | 35 |
| | 1 h 50 min | 90 |
| | 1 h 25 min | 80 |
| | 12 h 15 min | 50 |

Table 9 – SoA tests with oil fuel data gathering, fall 2011

| Date | Duration | Firing rate % |
|---|---|---|
| 1/11/2012 | 2 h 10 min | 25 |
| | 2 h 15 min | 25 |
| 1/12/2012 | 10 h 27 min | 35 |
| | 1 h 30 min | 25 |
| 1/13/2012 | 38 min | 25 |
| | 11 h 20 min | 25 |
| | 2 h 17 min | 30 |
| | 4 h | 40 |
| | 4 h 7 min | 50 |
| 1/14/2012 | 4 h 40 min | 50 |
| | 3 h 35 min | 70 |
| | 1 h | 70 |
| | 5 h 37 min | 70 |
| | 1 h 20 min | 80 |
| | 4 h 57 min | 55 |
| 1/15/2012 | 15 h 35 min | 55 |
| | 8 h 7 min | 55 |

### 5.4.4 "Legacy" Characterization

The need to perform a series of tests to replicate boiler operation relative to "legacy" pre-demonstration operation derived from the fact that oxygen concentration levels were not matching with historical data after that the boiler was recommissioned immediately before start of data collection. As the linkage controller could not be restored after switchover to the PPC4000, it was decided to operate the latter electronic control in "parallel positioning" mode, i.e. in open loop configuration with pre-set positions for the fuel and air servos across the firing

range to mimic linkage control. It was considered that an average excess oxygen concentration of 7% could correspond to historical operation and more common setup for boilers with linkage systems. Ultimately, the commissioning technician implemented a table with a minimum 4% $O_2$ concentration target as illustrated below.

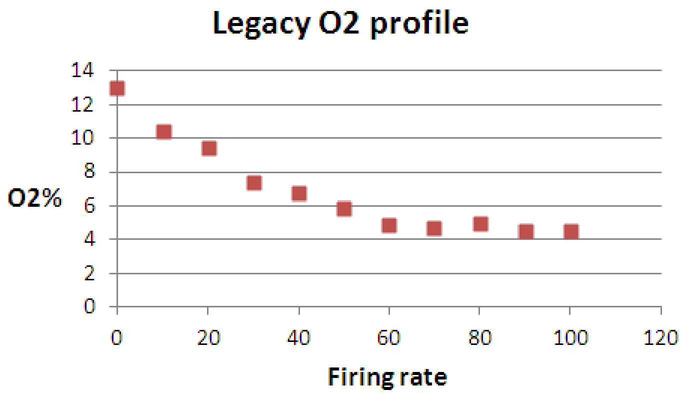



Figure 44 – Commissioning profile for “legacy” configuration.

Data was collected as follows:

Table 10 – “Legacy” setup natural gas data gathering

| Date | Duration | Firing Rate % |
|---|---|---|
| **16-Dec** | 1 h 17 min | 30 |
| | 6 h | 15 |
| | 2 h 40 min | 15 |
| | 1 h 10 min | 50 |
| | 12 h | 30 |
| **22-Dec** | 10 h 40 min | 50 |
| | 12 h 2 min | 30 |
| **23-Dec** | 6 h 50 min | 30 |
| | 1 h 27 min | 30 |
| | 4 h | 65 |
| | 6 h 30 min | 30 |
| | 4 h | 75 |
| **24-Dec** | 3 h 42 min | 75 |
| | 19 h 55 min | 50 |
| **25-Dec** | 23 h 57 min | 50 |
| **26-Dec** | 23 h 57 min | 50 |
| **27-Dec** | 6 h 52 min | 50 |
| | 2 h 37 min | 50 |
| | 14 h 2 min | 50 |

### 5.4.5 CO/O2 Trim Characterization

Setup and testing of the new CO/O2 trim control system followed a different approach, as:

- The control prototype, even if it was pre-tested at Fireye, it did not undergo extensive testing and UL certification process typical of a system released as product like the O2 trim system. For this reason, it was decided to operate the controller only in supervised mode, with a UTRC or Fireye test engineer overseeing the testing. This limited somewhat the duration of each test.
- The control algorithm requires tuning of additional parameters which are needed to set the functioning of the algorithm. As such tuning parameters require adaptation to the specific boiler, procedures for parameter setting were repeated to identify adequate parameterization.

For all other aspects of test startup and shutdown, the procedures illustrated in Section 5.4.2 for SoA testing were followed.

*Parameter calibration*

To operate the CO/O2 trim control system, the adjustment of new parameters in addition to those of the standard O2 trim solution is required. Such new parameters define the adjustment procedure of the $O_2$ concentration target as well as the micropulsing procedure (see Section 2.2.1). Additionally, the parameters which are common to the standard O2 trim algorithm need to be carefully tuned, as poor operation of the O2 trim loop would affect operation of the overall control system. Parameters that particularly impacted the algorithm operation are:

- *$O_2$ concentration target adjustment amplitudes (downward and upward) and frequency:* The $O_2$ concentration target is periodically adjusted downwards so that the boiler can progressively operate closer to the stoichiometric boundary. The adjustment period was set at long intervals (~10min) to enable settling of the O2 trim control loop. Downward adjustment amplitude was typically set at 0.1%, while upward adjustment at 0.2%. An upward adjustment occurs any time a CO spike exceeding the high CO limit is reached.
- *CO limits, high and low.* Setting of the CO limits was conservative, in order for the control system to respond to the onset of CO formation. The controller would stop adjusting the $O_2$ concentration target when a spike of 25ppm CO was recorded, and adjusted upwards is a spike of 45ppm was recorded.
- *Micropulsing frequency and magnitude:* Micropulsing is used to identify the proximity to the region where CO is formed. The selection of fuel pulse amplitude affects operation, as excessive values would induce the boiler to generate CO spikes even if the control is operating far enough from the stoichiometric boundary. In addition, periodic time of micropulsing needs to be smaller than the $O_2$ target adjustment time in order to be effective.
- *Trim limit and trim ratio:* These parameters are common with the O2 trim algorithm, and define the allowed range of positions of the air servo. The parameters effectively limit the trim function to avoid potentially unsafe conditions associated with the air servo reducing the air flow excessively. Tuning had to be carefully performed to ensure at the same time safe operation as well as allowing operation close enough to the stoichiometric region.
- *Proportional and Integral gains of the O2 trim loop:* Setting of the control loop need to be accurate, to avoid that the $O_2$ levels depart too much from the target. Additionally, tuning needs to be performed such that the control loop is not too “aggressive” to respond to rapid fuel flow and $O_2$ concentration changes associated with micropulsing.

The following settings for the PPC4000 controller were finally defined as acceptable for the demonstration. Parameters could be set and adjusted by means of the controller's user interface.

Table 11 – CO/O2 trim controller settings

| Parameter | Value |
|---|---|
| Trim limit | 8 |
| Trim limit ratio | 3 |
| CO limits (min/max) | 25ppm, 45ppm |
| Micropulsing frequency | 420 seconds |
| Micropulsing magnitude | 0.5° of fuel servo position |
| O2 adjustment period | 10 minutes |
| P-gain | 3 |
| I-Gain | 60 |

Collected data was limited to natural gas only, as no switchover to oil occurred at the arsenal during testing time. The following tests were performed:

Table 12 – CO/O2 trim operation with natural gas data gathering

| Date | Duration | Firing rate (%) |
|---|---|---|
| 6-Feb | 15 min | 55 |
| 8-Feb | 3 min | 70 |
| 8-Feb | 7 min | 70 |
| 13-Feb | 2 h | 60 |
| 15-Feb | 1hr 31 min | 40 |
| 15-Feb | 2 h 13 min | 45 |
| 17-Feb | 27 min | 40 |
| 17-Feb | 60 min | 40 |
| 22-Feb | 28 min | 25 |
| 22-Feb | 25 min | 30 |
| 5-Mar | 18 min | 90 |
| 5-Mar | 12 min | 75 |
| 6-Mar | 30 min | 55 |
| 6-Mar | 27 min | 40 |

### 5.4.6 Decommissioning

As agreed by Watervliet Arsenal, the demonstration equipment was partly left in place, partly decommissioned as follows:

1. The Fireye PPC4000 controller together with servomechanism, control unit and displays was left in place. The controller was brought back to the "O2 trim" state as follows:
    a. The Fireye CO/O2 sensor box was removed and the product PPC4000 O2 probe reconnected to the PPC4000 unit.
    b. A more recent product release of the PPC4000 unit software was updated to its newest product release, tested and recommissioned by Fireye.

    The changes described above left in place a UL certified product release of PPC4000.

2. All the process metering sensors including, among others, flow meters (steam, gas, oil), and temperature sensors, with the exclusion of the stack gas sensors (see “removed equipment” list) were left in place.

3. ALC data acquisition modules and wiring, including the I/O unit, the MODBUS unit, the data acquisition unit and the laptop server with the WEBCtrl data acquisition software and graphical interface was left in place.

The following equipment was decommissioned and removed from the boiler plant:

- The sensor rack located on the back of the boiler, including the NDIR CO sensor box.
- The multi-sensor box (CO, $O_2$, $NO_x$) labeled Forney together with all associated stack sampling probes.
- The multi-sensor box (CO, $O_2$) labeled Fireye together with all associated stack sampling probes.
- All gas calibration bottles, tools, regulators.
- The ETC oxygen probe.
- The 3G wireless link currently attached to the data acquisition laptop.

## 5.5 SAMPLING PROTOCOL

Sampling of performance related data has been specified in the previous section. Given that the timeframe for demonstration was limited by boiler availability during the heating season, collection of data for each phase was initially planned for the duration of two months, but for some configuration was shorter because of longer times than expected for development and installation. Acquisition of time series data initially occurred at a 1 second sampling interval, but early in the set up of the data acquisition system it was decided that a two second time sampling interval was sufficient and more amenable to collection of all the parameters desired. Two second interval sampling was then used during the execution of all tests. Compound metrics were calculated from those tests. A detailed table of dates and times for sampled data used in the analysis of performance is included in section 5.4. Post processing routines (i.e. noise filtering, scaling, performance metric computation) were created to process the measurement data for each experiment.

### 5.5.1 Calibration of Equipment

For the entire demonstration period a rack of laboratory-grade instruments identified in Table 13 was deployed and continuously sampled at 1Hz. During testing, 5 lpm of exhaust gas was pulled to the instruments through a 20 ft x ¼ in stainless steel sample line heated to 250°F using a standard bellows pump. In addition, for the instruments to operate continuously, a standard thermal electric sample gas conditioner (Universal Analzyers Inc., model 1060) was used to remove water by dropping the dew point to 41°F and condensing all the moisture from the sample stream which was then removed by a Masterflex peristaltic pump. This arrangement allowed 24/7 sampling of the exhaust.

Table 13 – List of Laboratory Grade Instruments

| # | Analzyer | Type | Instrument Range | Vendor and Model | process variable | Trend Interval |
|---|---|---|---|---|---|---|
| 1 | CO | NDIR | 0 to 500 ppm | Siemens UltraMet 22 | exhaust carbon monoxide | 1 sec |
| 2 | O2 | paramagnetic | 0 to 10 % | Beckman 755 | exhaust oxygen | 1 sec |
| 3 | CO2 | NDIR | 0 to 20,000 ppm | Siemens UltraMet 22 | exhaust carbon dioxide | 1 sec |
| 4 | NOx | Chemi | 0 to100 ppm | ThermoElectron M35G | exhaust NO + NO2 | 1 sec |
| 5 | NO | Chemi | 0 to100 ppm | ThermoElectron M35G | exhaust nitric oxide | 1 sec |
| 6 | NO2 | Chemi | 0 to100 ppm | ThermoElectron M35G | exhaust nitrogen dioxide | 1 sec |

Calibration was checked approximately once a week and adjustments were made for instrument drift if necessary. A zero calibration gas of 99.999% $N_2$ and appropriate span gases were used for each instrument (4.90% and 8.01% $O_2$ in $N_2$, 5.02% $CO_2$ in $N_2$, 201 ppmv CO in $N_2$, 75 ppmv NO in $N_2$, 100 ppmv $NO_2$ in $N_2$). These calibration bottles were kept on site for easy calibration. The laboratory instruments all had better than 1% linearity and repeatability, however some drift was observed and periodically corrected using the following procedure:

1. Zero gas introduced to the analyzer
2. Value displayed by GUI entered into a calibration utility spreadsheet
3. Span gas introduced to the analyzer
4. Value displayed by GUI entered into a calibration utility spreadsheet
5. Calibration utility uses the certified span gas concentration to compute slope and intercept
6. Slope and intercept are entered into the appropriate cells of the ALC software
7. Corrected analyzer concentration value is now displayed and recorded by DAQ system

This procedure is required to accurately log the analog output with the data logger vs. checking the zero and span at the instrument. The instrument rack is located approximately 30 ft from the analog to digital converter in the ALC cabinet. Checks and corrections were made on all instruments in the rack approximately weekly starting 10/29/2010 and ending 3/14/2012. Of all the instruments, the paramagnetic $O_2$ analyzer showed the most drift over time and typically a negative trend. Measured values when the instrument was re-calibrated are shown in Figure 45 for the first heating season starting in February 2011 and ending in April 2011. Although some drift is observed, the corrections are typically less than 0.3%.

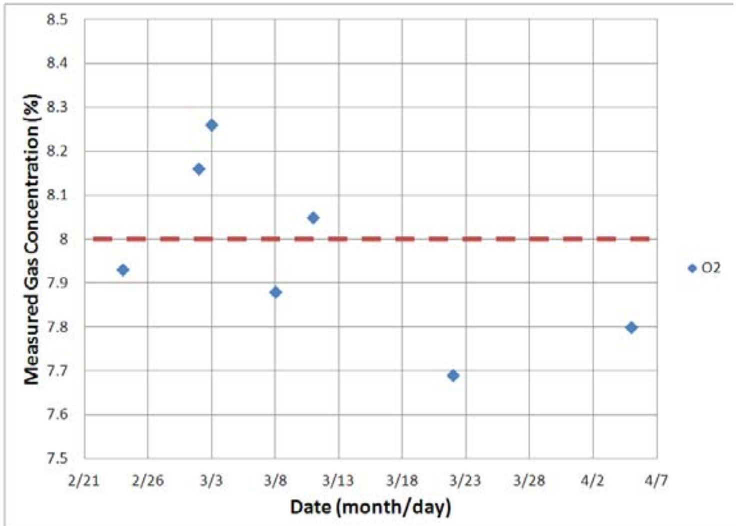



Figure 45 – Measured $O_2$ sensor drift

The Fireye in-situ sensors for $O_2$ were also calibrated by introducing a zero and span gas into calibration ports on those instruments. Correction for drift was performed using the same procedure as that used for the gas rack, however very little change to the initial slope and intercept was required for the in-situ sensors. A typical comparison of the two $O_2$ sensors is shown in Figure 46 showing agreement within 0.2% over a large change in exhaust $O_2$ concentration. (this is an in-use comparison, not comparison vs. a span gas.)

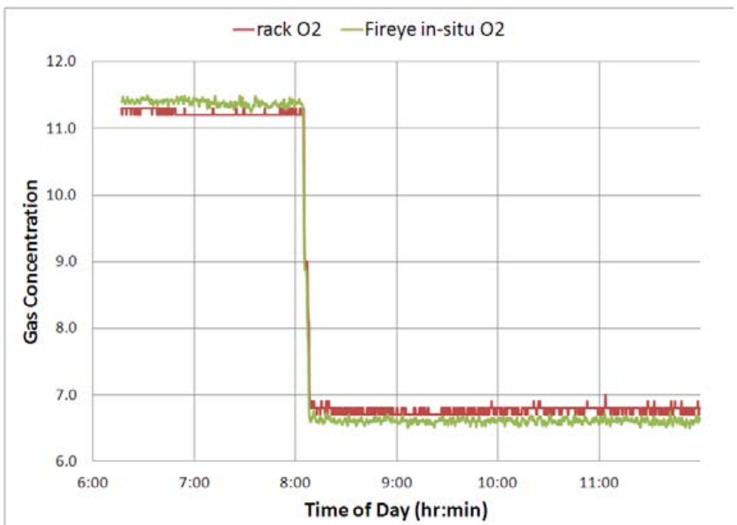



Figure 46 – Comparison of $O_2$ sensors illustrating agreement within 0.2%

Flow, temperature, pressure, and all sensors other than gas concentration sensors are factory calibrated and drift or mistuning was not expected for the duration of the demonstration, given typical manufacturer specifications for those types of sensor[2].

[2] http://www.foxthermalinstruments.com/pdfs/ft2/ft2.pdf; http://www.sailsors.com/www/pdf/VCA.pdf

### 5.5.2 Quality Assurance Sampling

Data quality (temporal resolution as well as accuracy) is a concern to fully understand the performance of control algorithms and includes time sampling aspects as well as experiment sampling. The base time sampling rate was 1 or 2 seconds. As a consequence, for long experiments the resulting data files became large. Therefore, data was generally down-sampled during the post-processing step to 2.5 minutes. The data for all summarized performance metrics included in Section 6.0 were loaded into Microsoft Excel, with the sample data files set up similarly for all control schemes. Performance calculations were executed in Excel. To ensure sampling quality, the following techniques were applied:

- Duplicates: During the development of the gas analysis system, cross-checking of the sensor candidates against more accurate lab-grade equipment will demonstrate specific sensor performances and improve quality of the data collected.
- Re-calibration: During field deployment, frequent re-calibration (and recording of sensor drift) was used to assure the accuracy of gas analysis data as described in section 5.5.1.

Temporal response of the exhaust gas sensors is shown in Figure 47 during a test where $O_2$ is trimming down. The $O_2$ signal is from the in-situ probe (blue) and the $CO_2$ signal is from the rack sensor (green). Close agreement between the two probes is illustrated and typical of the entire demonstration. For the same timeline the curves for $NO_x$ and CO are shown illustrating low values for each and the controller response to rising CO is also illustrated.

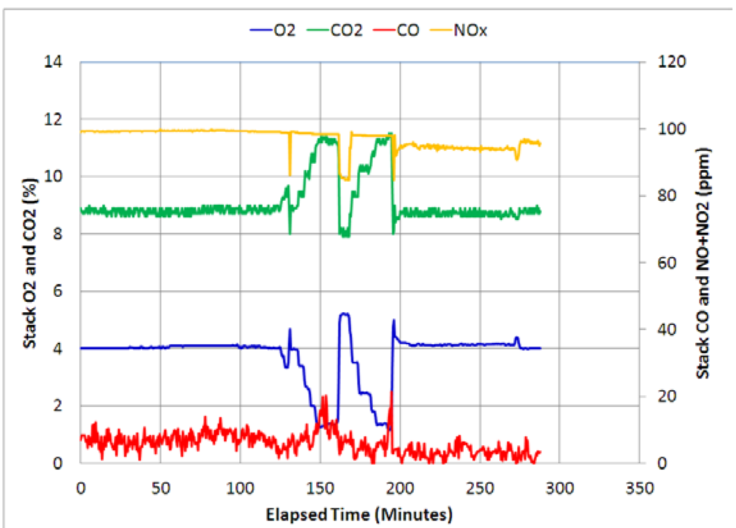



Figure 47 – Typical temporal response of the exhaust gas sensors

Calculation of boiler performance also requires an accurate measurement of the actual real-time fuel heating value. A complete daily analysis of the natural gas delivered to WVA via the Schenectady hub is available online from Dominion Transmission Inc. (DTI) (http://escript.dom.com/jsp/info_post.jsp?&company=dti). In addition to the daily DTI report, four samples of gas were also taken and analyzed at UTRC using a GC/FID for reconciliation purposes.

The daily higher heating value (HHV) for the natural gas reported by DTI over the entire demonstration test period is shown in Figure 48. Although the data shows some variation, the HHV is surprisingly constant over the entire test period. The daily value was used in calculations of boiler performance and in the plots reported herein.

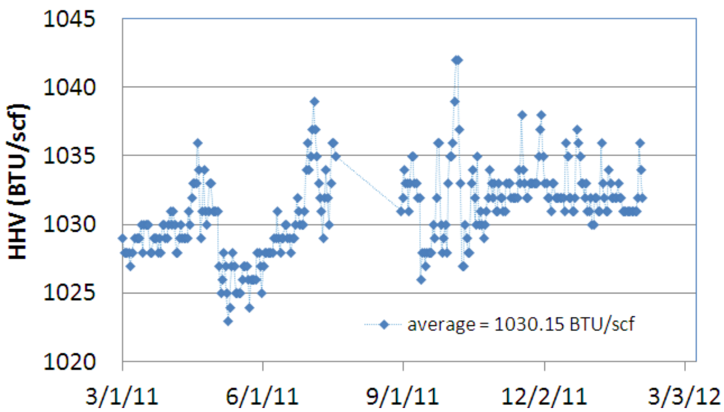



Figure 48 –Daily Higher Heating Value of Natural Gas at Schenectady reported by Dominion

At UTRC a gas chromatograph (GC) was used to separate the individual gas species which were then analyzed with a standard flame ionization detector (FID) to determine hydrocarbon concentrations. Samples were taken at WVA on 11/4/2011, 12/14/2011, 1/12/2012 and 2/1/2012. On each day a sample was taken upon arrival at WVA, typically before 10AM, and prior to leaving at about 5PM. The results are compared for the major hydrocarbon species in Figure 50. Agreement between the UTRC analysis and the DTI report is very good in all cases reinforcing the validity of using the daily HHV reported by DTI.

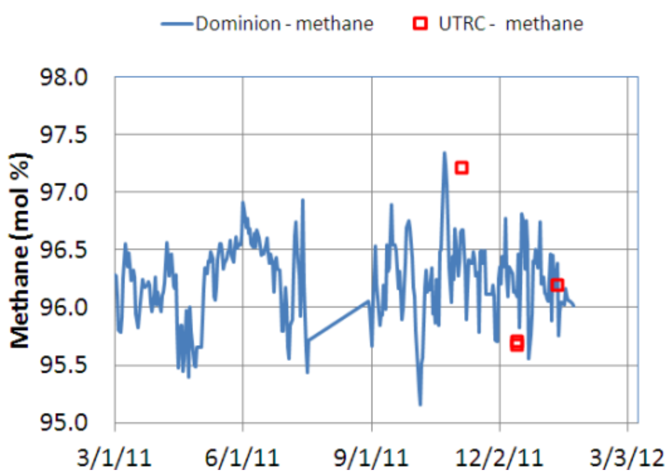



Figure 49 – Comparison of UTRC and DTI gas species concentrations: methane

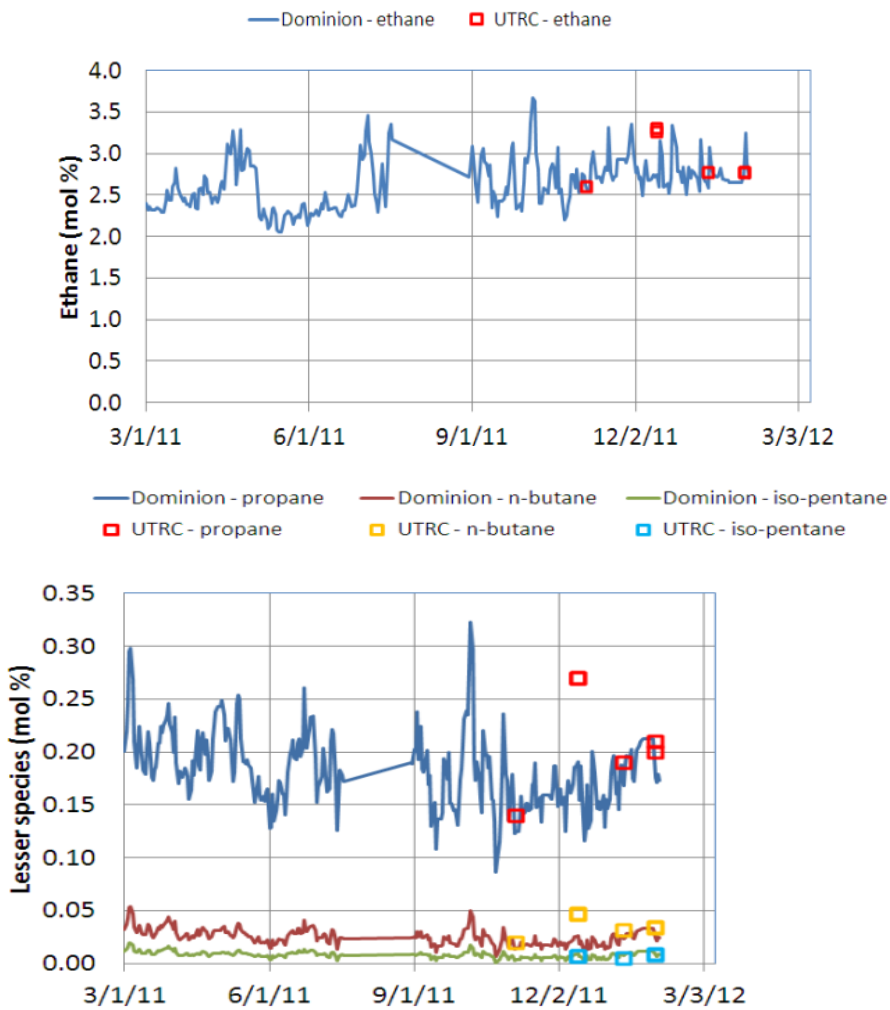



Figure 50 – Comparison of UTRC and DTI gas species concentrations: other species

## 5.6 SAMPLING RESULTS

The original test plan was to measure the baseline performance of the Watervliet boiler system using the newly installed data acquisition system and all necessary instrumentation prior to recommissioning with Fireye's PPC4000 combustion control system. Subsequently, the mechanical linkage of the baseline system would be replaced by air and fuel servos controlled by the (also newly installed) Fireye PPC4000 burner control system. At that time, a new commissioning would be done, in order to clearly distinguish baseline operation, with preset fuel and air settings provided through mechanical linkages, from the PPC4000 control of air and fuel servos where the $O_2$ level is maintained at the commissioned fuel/air settings. Performance tests would then be repeated with the PPC4000 (designated in all figures and tables herein as either the SoA or O2 trim control system).

In order to minimize any disruption to the Arsenal's normal boiler operations, UTRC personnel coordinated data acquisition at various firing rates within the steam supply needs of the Arsenal and the weather conditions that affect those needs. As a result, the steady state intervals at

constant firing rates vary in length, time and date of occurrence, and number of repeated trials at each firing rate. However, the data taken spans the range specified in the performance objectives, as they were obtained using the three control systems over a range of firing rates.

Most of the data are for natural gas combustion. The Arsenal has an interruptible fuel service contract, whereby they are told when to switch over to oil operation. Due to weather conditions, during the testing time of this program, there were a limited number of days during which oil was used. Data within 40-80% of maximum fuel flow rate was captured, providing an indication of system performance which was extrapolated to calculate overall performance metrics. The acquisition of additional data would have required an extension of the demonstration to the 2012-2013 heating season, but would have provided information across the full firing range and, if taken during different weather conditions, provided a better idea of the effect of weather variability on performance with oil.

During the first heating season, sample data was taken during February through April, 2011. For most of that time, data is available for the full 24 hours. Table 14 shows the days for which data was recorded, processed into Microsoft Excel, plotted and used for analysis of boiler performance, along with other related information distinguishing important characteristics.

Table 14 – Sampling Results Available and Analyzed for Boiler Performance

| Control System | Test Date | Time Duration of Steady State Interval | Fuel |
|---|---|---|---|
| Baseline | 2/22/2011 | 1 h 32 min | oil |
| Baseline | 2/22/2011 | 1 h 30 min | oil |
| Baseline | 2/22/2011 | 1 h 32 min | oil |
| Baseline | 2/22-23/2011 | 16 h 40 min | oil |
| Baseline | 2/23/2011 | 1 h 18 min | oil |
| Baseline | 2/23/2011 | 2 h 50 min | oil |
| Baseline | 2/23/2011 | 1 h 37 min | oil |
| Baseline | 2/23/2011 | 3 h 40 min | oil |
| Baseline | 2/23/2011 | 2 h 47 min | oil |
| Baseline | 2/23/11-2/24/2011 | 11 h 32 min | oil |
| Baseline | 3/2/2011 | 1 h 25 min | oil |
| Baseline | 3/2/2011 | 9 h 55 min | oil |
| Baseline | 3/3/2011 | 1 h 21 min | oil |
| Baseline | 3/3/2011 | 4 h 20 min | oil |
| Baseline | 3/3/2011 | 2 h | oil |
| Baseline | 3/3/11-3/4/2011 | 18 h 20 min | oil |
| Baseline | 3/4/2011 | 1 h 27 min | oil |
| Baseline | 3/5/2011 | 24hr | natural gas |
| Baseline | 3/6/2011 | 14hr 35min | natural gas |
| Baseline | 3/6/2011 | 4hr 58min | natural gas |
| Baseline | 3/6/2011 | 1hr 10min | natural gas |
| Baseline | 3/7/2011 | 24hr | natural gas |
| Baseline | 3/8/2011 | 2hr 45min | natural gas |

| Control System | Test Date | Time Duration of Steady State Interval | Fuel |
|---|---|---|---|
| Baseline | 3/8/2011 | 40min | natural gas |
| Baseline | 3/8/2011 | 1hr 38min | natural gas |
| Baseline | 3/8/2011 | 1hr 40min | natural gas |
| Baseline | 3/8/2011 | 6hr 2min | natural gas |
| Baseline | 3/8/2011 | 1hr 40min | natural gas |
| Baseline | 3/8/2011 | 1hr 20min | natural gas |
| Baseline | 3/8/2011 | 1hr 25min | natural gas |
| Baseline | 3/8/2011 | 47min | natural gas |
| Baseline | 3/92011 | 3hr 18min | natural gas |
| Baseline | 3/92011 | 1hr 20min | natural gas |
| Baseline | 3/92011 | 1hr 27min | natural gas |
| Baseline | 3/92011 | 1hr 28min | natural gas |
| Baseline | 3/10/2011 | 9hr 50min | natural gas |
| Baseline | 3/10/2011 | 25min | natural gas |
| Baseline | 3/10/2011 | 1hr 5min | natural gas |
| Baseline | 3/10/2011 | 1hr 20min | natural gas |
| Baseline | 3/10/2011 | 1hr 7min | natural gas |
| Baseline | 3/10/2011 | 1hr 35min | natural gas |
| Baseline | 3/10/2011 | 4hr 30min | natural gas |
| Baseline | 3/11/2011 | 4hr 42min | natural gas |
| Baseline | 3/12/2011 | 15hr 47min | natural gas |
| Baseline | 3/12/2011 | 3hr 2min | natural gas |
| Baseline | 3/13/2011 | 9hr | natural gas |
| Baseline | 3/13/2011 | 58min | natural gas |
| Baseline | 3/13/2011 | 1hr 12min | natural gas |
| Baseline | 3/13/2011 | 13min | natural gas |
| Baseline | 3/13/2011 | 1hr 17min | natural gas |
| Baseline | 3/14/2011 | 3hr 12min | natural gas |
| Baseline | 3/14/2011 | 22min | natural gas |
| Baseline | 3/14/2011 | 33min | natural gas |
| Baseline | 3/14/2011 | 5hr 5min | natural gas |
| Baseline | 3/14/2011 | 38min | natural gas |
| Baseline | 3/14/2011 | 5hr 32min | natural gas |
| Baseline | 3/15/2011 | 8hr 7min | natural gas |
| Baseline | 3/15/2011 | 7hr 52min | natural gas |
| Baseline | 3/16/2011 | 6hr 32min | natural gas |
| Baseline | 3/16/2011 | 5hr 57min | natural gas |
| Baseline | 3/16/2011 | 1hr 55min | natural gas |
| Baseline | 3/16/2011 | 1hr 38min | natural gas |
| Baseline | 3/16/2011 | 4hr 35min | natural gas |

| Control System | Test Date | Time Duration of Steady State Interval | Fuel |
|---|---|---|---|
| Baseline | 3/17/2011 | 9hr 10min | natural gas |
| Baseline | 3/17/2011 | 2hr 35min | natural gas |
| Baseline | 3/17/2011 | 5hr 22min | natural gas |
| Baseline | 3/18/2011 | 6hr 57min | natural gas |
| Baseline | 3/18/2011 | 10hr 23min | natural gas |
| Baseline | 3/18/2011 | 5hr 10min | natural gas |
| Baseline | 3/19/2011 | 3hr 44min | natural gas |
| Baseline | 3/19/2011 | 1hr 10min | natural gas |
| Baseline | 3/19/2011 | 30min | natural gas |
| Baseline | 3/19/2011 | 1hr | natural gas |
| Baseline | 3/19/2011 | 1hr 22min | natural gas |
| Baseline | 3/19/2011 | 50min | natural gas |
| Baseline | 3/19/2011 | 3hr 25min | natural gas |
| Baseline | 3/20/2011 | 2hr 32min | natural gas |
| Baseline | 3/20/2011 | 1hr 23min | natural gas |
| Baseline | 3/20/2011 | 1hr 23min | natural gas |
| Baseline | 3/20/2011 | 1hr 12min | natural gas |
| Baseline | 3/20/2011 | 10hr 30min | natural gas |
| Baseline | 3/21/2011 | 6hr 32min | natural gas |
| Baseline | 3/21/2011 | 42min | natural gas |
| Baseline | 3/21/2011 | 5hr 40min | natural gas |
| Baseline | 3/22/2011 | 4hr 38min | natural gas |
| Baseline | 3/22/2011 | 2hr 52min | natural gas |
| Baseline | 3/22/2011 | 25min | natural gas |
| Baseline | 3/22/2011 | 1hr 40min | natural gas |
| Baseline | 3/22/2011 | 1hr 8min | natural gas |
| Baseline | 3/22/2011 | 2hr 5min | natural gas |
| Baseline | 3/22/2011 | 37min | natural gas |
| Baseline | 3/22/2011 | 40 min | natural gas |
| Baseline | 3/22/2011 | 1hr | natural gas |
| Baseline | 3/22/2011 | 1hr 7min | natural gas |
| Baseline | 3/22/2011 | 2hr 37min | natural gas |
| Baseline | 3/23/2011 | 3hr 33min | natural gas |
| Baseline | 3/23/2011 | 2hr 8min | natural gas |
| Baseline | 3/25/2011 | 9hr 35min | natural gas |
| Baseline | 3/25/2011 | 2hr 35min | natural gas |
| Baseline | 3/25/2011 | 50min | natural gas |
| Baseline | 3/25/2011 | 5hr 17min | natural gas |
| O2 trim - SoA | 4/14/2011 | 3hr 13min | natural gas |
| O2 trim - SoA | 4/14/2011 | 7hr 15min | natural gas |

| Control System | Test Date | Time Duration of Steady State Interval | Fuel |
|---|---|---|---|
| O2 trim - SoA | 4/15/2011 | 7hr 2min | natural gas |
| O2 trim - SoA | 4/15/2011 | 42min | natural gas |
| O2 trim - SoA | 4/15/2011 | 1hr 15min | natural gas |
| O2 trim - SoA | 4/15/2011 | 2hr 30min | natural gas |
| O2 trim - SoA | 4/15/2011 | 6hr 48min | natural gas |
| O2 trim - SoA | 4/16/2011 | 7hr 47min | natural gas |
| O2 trim - SoA | 4/16/2011 | 10hr 50min | natural gas |
| O2 trim - SoA | 4/17/2011 | 24hr | natural gas |
| O2 trim - SoA | 4/18/2011 | 9hr 30min | natural gas |
| O2 trim - SoA | 4/18/2011 | 10hr 42min | natural gas |
| O2 trim - SoA | 4/19/2011 | 7hr 15min | natural gas |
| O2 trim - SoA | 4/19/2011 | 1hr 13min | natural gas |
| O2 trim - SoA | 4/19/2011 | 1hr 45min | natural gas |
| O2 trim - SoA | 4/19/2011 | 12hr 7min | natural gas |
| O2 trim - SoA | 4/20/2011 | 24hr | natural gas |
| O2 trim - SoA | 4/21/2011 | 24hr | natural gas |
| O2 trim - SoA | 4/22/2011 | 23hr 27min | natural gas |
| O2 trim - SoA | 4/23/2011 | 2hr 15min | natural gas |
| O2 trim - SoA | 4/23/2011 | 3hr 42min | natural gas |
| O2 trim - SoA | 4/23/2011 | 3hr 20min | natural gas |
| O2 trim - SoA | 4/23/2011 | 11hr 30min | natural gas |
| O2 trim - SoA | 4/24/2011 | 1hr 7min | natural gas |
| O2 trim - SoA | 4/24/2011 | 2hr 40min | natural gas |
| O2 trim - SoA | 4/24/2011 | 19hr 50min | natural gas |
| O2 trim - SoA | 4/25/2011 | 1hr 3min | natural gas |
| O2 trim - SoA | 4/25/2011 | 2hr 8min | natural gas |
| O2 trim - SoA | 4/25/2011 | 19hr 15min | natural gas |
| O2 trim - SoA | 4/26/2011 | 1hr 37min | natural gas |
| O2 trim - SoA | 4/26/2011 | 3hr 42min | natural gas |
| O2 trim - SoA | 4/26/2011 | 1hr 55min | natural gas |
| O2 trim - SoA | 4/26/2011 | 15hr 48min | natural gas |
| O2 trim - SoA | 4/27/2011 | 1hr 45min | natural gas |
| O2 trim - SoA | 4/27/2011 | 8hr 18min | natural gas |
| O2 trim - SoA | 4/27/2011 | 11hr | natural gas |
| O2 trim - SoA | 10/29/2011 | 2 h 2 min | natural gas |
| O2 trim - SoA | 10/29/2011 | 1 h 57min | natural gas |
| O2 trim - SoA | 10/29/2011 | 1 h 57min | natural gas |
| O2 trim - SoA | 10/29/2011 | 9 h 45 min | natural gas |
| O2 trim - SoA | 10/30/2011 | 24 h | natural gas |
| O2 trim - SoA | 10/312011 | 7 h 55 min | natural gas |

| Control System | Test Date | Time Duration of Steady State Interval | Fuel |
|---|---|---|---|
| O2 trim - SoA | 10/312011 | 1 h 58 min | natural gas |
| O2 trim - SoA | 10/312011 | 1 h 50 min | natural gas |
| O2 trim - SoA | 10/312011 | 1 h 15 min | natural gas |
| O2 trim - SoA | 10/312011 | 27 min | natural gas |
| O2 trim - SoA | 10/312011 | 9 h 5 min | natural gas |
| O2 trim - SoA | 11/3/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/4/2011 | 15 h 10 min | natural gas |
| O2 trim - SoA | 11/4/2011 | 5 h 47 min | natural gas |
| O2 trim - SoA | 11/5/2011 | 23 h 20 min | natural gas |
| O2 trim - SoA | 11/6/2011 | 23 h 22 min | natural gas |
| O2 trim - SoA | 11/11/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/12/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/13/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/15/2011 | 7 h 42 min | natural gas |
| O2 trim - SoA | 11/15/2011 | 2 h | natural gas |
| O2 trim - SoA | 11/15/2011 | 3 h 58 min | natural gas |
| O2 trim - SoA | 11/15/2011 | 5 h 23 min | natural gas |
| O2 trim - SoA | 11/16/2011 | 22 h 35 min | natural gas |
| O2 trim - SoA | 11/17/2011 | 22 h 45 min | natural gas |
| O2 trim - SoA | 11/18/2011 | 8 h 47 min | natural gas |
| O2 trim - SoA | 11/18/2011 | 1 h 58 min | natural gas |
| O2 trim - SoA | 11/18/2011 | 1 h 55 min | natural gas |
| O2 trim - SoA | 11/18/2011 | 2 h | natural gas |
| O2 trim - SoA | 11/18/2011 | 1 h 55 min | natural gas |
| O2 trim - SoA | 11/19/2011 | 3 h 43 min | natural gas |
| O2 trim - SoA | 11/19/2011 | 6 h 55 min | natural gas |
| O2 trim - SoA | 11/19/2011 | 12 h 40 min | natural gas |
| O2 trim - SoA | 11/20/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/21/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/22/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/23/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/24/2011 | 7 h 35 min | natural gas |
| O2 trim - SoA | 11/24/2011 | 1 h 45 min | natural gas |
| O2 trim - SoA | 11/24/2011 | 1 h 43 min | natural gas |
| O2 trim - SoA | 11/24/2011 | 1 h 52 min | natural gas |
| O2 trim - SoA | 11/24/2011 | 9 h 45 min | natural gas |
| O2 trim - SoA | 11/25/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/26/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 11/27/2011 | 23 h 57 min | natural gas |
| O2 trim - SoA | 12/6/2011 | 3 h 57 min | natural gas |

| Control System | Test Date | Time Duration of Steady State Interval | Fuel |
|---|---|---|---|
| O2 trim - SoA | 12/6/2011 | 19 h 37 min | natural gas |
| O2 trim - SoA | 12/7/2011 | 23 h 40 min | natural gas |
| O2 trim - SoA | 12/8/2011 | 4 h | natural gas |
| O2 trim - SoA | 12/8/2011 | 5 h 30 min | natural gas |
| O2 trim - SoA | 12/8/2011 | 1 h 32 min | natural gas |
| O2 trim - SoA | 12/8/2011 | 2 h | natural gas |
| O2 trim - SoA | 12/8/2011 | 5 h 28 min | natural gas |
| O2 trim - SoA | 12/9/2011 | 7 h 32 min | natural gas |
| O2 trim - SoA | 12/9/2011 | 40 min | natural gas |
| O2 trim - SoA | 12/9/2011 | 2 h 25 min | natural gas |
| O2 trim - SoA | 12/9/2011 | 45 min | natural gas |
| O2 trim - SoA | 12/9/2011 | 2 h 45 min | natural gas |
| O2 trim - SoA | 12/9/2011 | 3 h 52 min | natural gas |
| O2 trim - SoA | 12/9/2011 | 1 h 47 min | natural gas |
| O2 trim - SoA | 12/10/2011 | 7 h 22 min | natural gas |
| O2 trim - SoA | 12/10/2011 | 2 h 40 min | natural gas |
| O2 trim - SoA | 12/10/2011 | 11 h 12 min | natural gas |
| O2 trim - SoA | 12/11/2011 | 3 h 32 min | natural gas |
| O2 trim - SoA | 12/11/2011 | 2 h 58 min | natural gas |
| O2 trim - SoA | 12/11/2011 | 3 h 8 min | natural gas |
| O2 trim - SoA | 12/11/2011 | 1 h 35 min | natural gas |
| O2 trim - SoA | 12/11/2011 | 3 h 47 min | natural gas |
| O2 trim - SoA | 12/11/2011 | 3 h 25 min | natural gas |
| O2 trim - SoA | 12/12/2011 | 3 h 22 min | natural gas |
| O2 trim - SoA | 12/12/2011 | 3 h 18 min | natural gas |
| O2 trim - SoA | 12/12/2011 | 3 h 40 min | natural gas |
| O2 trim - SoA | 12/12/2011 | 1 h 25 min | natural gas |
| O2 trim - SoA | 12/12/2011 | 3 h 52 min | natural gas |
| O2 trim - SoA | 12/12/2011 | 3 h 42 min | natural gas |
| O2 trim - SoA | 12/13/2011 | 3 h 47 min | natural gas |
| O2 trim - SoA | 12/13/2011 | 3 h 10 min | natural gas |
| O2 trim - SoA | 12/13/2011 | 1 h 50 min | natural gas |
| O2 trim - SoA | 12/13/2011 | 1 h 25 min | natural gas |
| O2 trim - SoA | 12/13/2011 | 12 h 15 min | natural gas |
| Legacy (baseline) | 12/16/2011 | 1 h 17 min | natural gas |
| Legacy (baseline) | 12/16/2011 | 6 h | natural gas |
| Legacy (baseline) | 12/16/2011 | 2 h 40 min | natural gas |
| Legacy (baseline) | 12/16/2011 | 1 h 10 min | natural gas |
| Legacy (baseline) | 12/16/2011 | 12 h | natural gas |
| Legacy (baseline) | 12/22/2011 | 10 h 40 min | natural gas |

| Control System | Test Date | Time Duration of Steady State Interval | Fuel |
|---|---|---|---|
| Legacy (baseline) | 12/22/2011 | 12 h 2 min | natural gas |
| Legacy (baseline) | 12/23/2011 | 6 h 50 min | natural gas |
| Legacy (baseline) | 12/23/2011 | 1 h 27 min | natural gas |
| Legacy (baseline) | 12/23/2011 | 4 h | natural gas |
| Legacy (baseline) | 12/23/2011 | 6 h 30 min | natural gas |
| Legacy (baseline) | 12/23/2011 | 4 h | natural gas |
| Legacy (baseline) | 12/24/2011 | 3 h 42 min | natural gas |
| Legacy (baseline) | 12/24/2011 | 19 h 55 min | natural gas |
| Legacy (baseline) | 12/25/2011 | 23 h 57 min | natural gas |
| Legacy (baseline) | 12/26/2011 | 23 h 57 min | natural gas |
| Legacy (baseline) | 12/27/2011 | 6 h 52 min | natural gas |
| Legacy (baseline) | 12/27/2011 | 2 h 37 min | natural gas |
| Legacy (baseline) | 12/27/2011 | 14 h 2 min | natural gas |
| O2 trim - SoA | 1/11/2012 | 2 h 10 min | oil |
| O2 trim - SoA | 1/11/2012 | 2 h 15 min | oil |
| O2 trim - SoA | 1/12/2012 | 10 h 27 min | oil |
| O2 trim - SoA | 1/12/2012 | 1 h 30 min | oil |
| O2 trim - SoA | 1/13/2012 | 38 min | oil |
| O2 trim - SoA | 1/13/2012 | 11 h 20 min | oil |
| O2 trim - SoA | 1/13/2012 | 2 h 17 min | oil |
| O2 trim - SoA | 1/13/2012 | 4 h | oil |
| O2 trim - SoA | 1/13/2012 | 4 h 7 min | oil |
| O2 trim - SoA | 1/14/2012 | 4 h 40 min | oil |
| O2 trim - SoA | 1/14/2012 | 3 h 35 min | oil |
| O2 trim - SoA | 1/14/2012 | 1 h | oil |
| O2 trim - SoA | 1/14/2012 | 5 h 37 min | oil |
| O2 trim - SoA | 1/14/2012 | 1 h 20 min | oil |
| O2 trim - SoA | 1/14/2012 | 4 h 57 min | oil |
| O2 trim - SoA | 1/15/2012 | 15 h 35 min | oil |
| O2 trim - SoA | 1/15/2012 | 8 h 7 min | oil |
| CO/O2 trim | 2/6/2012 | 15 min | natural gas |
| CO/O2 trim | 2/8/2012 | 3 min | natural gas |
| CO/O2 trim | 2/8/2012 | 7 min | natural gas |
| CO/O2 trim | 2/13/2012 | 2 h | natural gas |
| CO/O2 trim | 2/15/2012 | 1hr 31 min | natural gas |
| CO/O2 trim | 2/15/2012 | 2 h 13 min | natural gas |
| CO/O2 trim | 2/17/2012 | 27 min | natural gas |
| CO/O2 trim | 2/17/2012 | 60 min | natural gas |
| CO/O2 trim | 2/22/2012 | 28 min | natural gas |
| CO/O2 trim | 2/22/2012 | 25 min | natural gas |

| Control System | Test Date | Time Duration of Steady State Interval | Fuel |
|---|---|---|---|
| CO/O2 trim | 3/5/2012 | 18 min | natural gas |
| CO/O2 trim | 3/5/2012 | 12 min | natural gas |
| CO/O2 trim | 3/6/2012 | 30 min | natural gas |
| CO/O2 trim | 3/6/2012 | 27 min | natural gas |

Two second interval data was processed and analyzed to look at transients, detailed control system behavior (mainly for the CO/O2 trim control system) and for gas sampling behavior during calibration and whenever running at very low excess air conditions. Plots were used to examine general dynamic behavior for each operating conditions and to determine time intervals useful for steady state performance analysis.

Table 15 contains the sampled parameters recorded during boiler operation. Some additional parameters that were recorded during the second heating season as a result of analysis of the first set of measurements are included at the bottom. In some instances, the order of a few of the parameters was changed; however, column headings can be used to ensure understanding of each data file, all of which will be provided along with this report.

Table 15 – Parameters sampled during burner control system tests

| Column Heading | Units | Description | Comments |
|---|---|---|---|
| secOfDay | seconds | Time of day | Some files may have additional time columns w/other units |
| Temp_Air_Deg_F | Fahrenheit | Inlet air temperature | Boiler room air |
| Temp_Water_Deg_F | Fahrenheit | Water temp in | |
| Temp_Stack_Deg_F | Fahrenheit | Exhaust stack temp | |
| ETC O2__% (wet basis) | Percent | Volume percentage of oxygen in exhaust air (includes water vapor) | |
| Combustion_Efficiency_p | Percent | **Disregard this value**; – from equipment which was not calibrated for fuel, conditions | |
| Steam_Pressure_psi | PSIG | Steam delivery pressure | Fairly constant, but still recorded |
| Mass_Flow_Gas_cufthr | Standard Cubic feet/hour | Natural gas flow | |
| Mass_Flow_Oil_galmin | Gallons/minute | No. 2 oil flow | |
| Mass_Flow_Water_lbmhr | Pounds/hour | Supply water flow into boiler | |
| Mass_Flow_Steam_lbmhr | Pounds/hour | Steam flow out of boiler | |
| RtoAuto | 0/1 | N/A | Indicator never used – not recorded during |

| Column Heading | Units | Description | Comments |
|---|---|---|---|
| | | | second season |
| Burner_On | Same as above | Same as above | Same as above |
| Fuel_Type_Gas | Same as above | Same as above | Same as above |
| Fuel_Type_Oil | Same as above | Same as above | Same as above |
| Low_Fire | Same as above | Same as above | Same as above |
| Purge | Same as above | Same as above | Same as above |
| CO__rack__ppm | ppm | CO in stack | UTRC sensor |
| O2__rack__% | Percent | O2 in stack (dry) | UTRC sensor |
| CO2__rack__% | Percent | CO2 in stack (dry) | UTRC sensor |
| NO__rack__ppm | ppm | NO in stack | UTRC sensor |
| NO2__rack__ppm | ppm | NO2 in stack | UTRC sensor |
| NOx__rack__ppm | ppm | (NO+NO2) in stack | UTRC sensor |
| Steam Temperature' | Fahrenheit | Provided check on steam quality in $2^{nd}$ runs | |
| NDIR CO PPM | ppm | Only sporadically available in data | |
| Duffy CO PPM | ppm | Only sporadically available in data | |
| Duffy CO2 PPM | ppm | Only sporadically available in data | |
| Duffy O2 % | Percent | Only sporadically available in data | |
| Duffy NOx PPM | Ppm | Only sporadically available in data | |
| Fireye O2 % | Percent | Reading returned by Fireye CO/O2 sensor | |
| Fireye O2 % Target | percent | Target set by Fireye sensor | |
| FIREYE CO PPM | ppm | Reading returned by Fireye CO/O2 sensor | |
| Fireye NOx PPM | ppm | Reading returned by Fireye CO/O2 sensor | |
| Fireye Mass Flow | | Commissioned firing rate set by Fireye | |

All calculations were executed on Excel spreadsheet to assess performance. Process data was then plotted on charts, and a visual determination made as to which portions of the data collected was part of a steady state. Once a subset of data was extracted for steady state performance assessment, averages and standard deviations were calculated. These interval values for the important parameters and metrics were then copied into a summary file where the overall performance could be compared over time, as duplicate samples and between different types of control systems. Plots in the summary Excel file include those shown in Section 6.

# 6. PERFORMANCE ASSESSMENT

Assessment of performance metrics was largely conducted by using data collected during tests on the demonstration boiler between February 2011 and March 2012. During preliminary analysis of data collected through April 2011, it was observed that some of the instrumentation used for data collection required repositioning to avoid inconsistencies in measurements (Section 5.4). Repositioning and modifications to sensors occurred in August and September 2011.

Because of these changes, the performance results presented below are separated into two sets. The first set includes natural gas data for baseline, mechanical linkage operation from March 2011 compared and SoA O2 trim operation from April 2011 (termed "1$^{st}$ set"). Instrumentation readings for this set were corrected for consistency with new data collected after sensor repositioning. The second set includes the three combustion control schemes: legacy, O2 trim SoA (termed "2$^{nd}$ set"), and CO/O2 trim, with natural gas. As explained in Section 5.4, legacy data were acquired with the PPC4000 control system in open loop (parallel positioning) mode replicating the behavior of the boiler with historical oxygen levels. The analysis revealed that legacy data were representative of boiler operation with about 4% oxygen at full load. Analysis was also performed for operation with No. 2 fuel oil with the linkage-based system and the PPC4000 O2 trim control system. CO/O2 trim operation with oil was not collected as a plant switchover to oil did not occur during demonstration.

An important consideration when comparing data taken using different combustion control systems and configurations over a long period of time relates to the definition of firing rates. The firing rate is a command variable to the boiler controller that corresponds to a desired power level. At commissioning, the installer set a high fire position, or 100% firing rate, at maximum boiler output, and a low fire position, or 0% firing rate, at the turndown limit of the boiler. The firing range 0%-100% is used for operating the boiler. As during the demonstration commissioning and modifications to positioning curves were implemented at each changeover by different installers with different weather conditions, it was not possible to keep the firing range consistent. For this reason, the firing rate was not used for comparison, but rather the % value of the maximum fuel flow rate, which is independent on operation.

An assessment of all performance metrics presented in Section 3 is summarized in the following Table and discussed in detail in the remainder of this section.

Table 16 – Performance objectives assessment summary

| Performance Objective | Metric | Pre-demonstration Success Criteria | Assessment summary |
|---|---|---|---|
| **Quantitative Performance Objectives** | | | |
| Improve Energy Efficiency | Short and long-term fuel to steam efficiency | >5% improvement over baseline;<br>>1.8% improvement over SoA | Natural gas: +2-4% over baseline, +0.5% and 1.5% over SoA observed at lower firing rates for well maintained boiler.<br>Oil: observed for SoA only. Improvement of 6-8% over baseline. |

| Performance Objective | Metric | Pre-demonstration Success Criteria | Assessment summary |
|---|---|---|---|
| Reduce Carbon Emissions | Short and long-term fuel to steam efficiency | >5% improvement over baseline;<br>>1.8% improvement over SoA | Natural gas: CO2 yearly emissions reduction estimated at 363,000 lb (181.5 ton), or 4%<br>Oil with O2 trim, CO2 yearly emissions can be reduced by 784,000 lb (392 ton) on a 25 MMBtu/h boiler, or 7%. |
| Increase combustion efficiency | Combustion efficiency over entire operating envelope (firing range) | >6% improvement over baseline;<br>>2% improvement over SoA | Natural gas: +1.5-3% over baseline, +0.5% and 1.5% over SoA observed at lower firing rates for well maintained boiler.<br>Oil: observed for SoA only. Improvement of 6-8% over baseline. |
| Meet CO, NOx regulatory emission requirements | Measured exhaust gas composition (CO, NOx) | Meet or exceed emission targets. | Met emission targets for $NO_x$ (below 120ppm) and CO (below 15ppm), on average basis. |
| Reduce controls commissioning time | Measured time to set air/fuel positions over boiler firing range | 30% reduction over baseline | Not measured directly. Qualitative assessment of setting the PPC4000 via graphical interface was observed. Overall, commissioning procedure lasted less than 2 hours, but were not typical of actual commissioning. |
| Reduce system operating costs | fuel costs, yearly operating costs for maintenance, tuning and commissioning | >5% improvement over baseline;<br>>1.8% improvement over SoA | 3.6% over baseline, 0.6% over SoA for natural gas. Not quantified for operation with oil (6.5% improvement SoA over baseline). |
| Verify sensor reliability | measurement errors and drift over time | Drift of sensors (CO, NOx) less than 5%/demo period (full range), no failures during demonstration time | Measured drift was always below 5% so that recalibration was not needed. The CO sensor did not fail during operation. |
| Ensure system availability | Equipment operational or ready to operate | >95% after installation completed (for prototype) | System was available throughout the demonstration which lasted one year. Downtime of 12 hours was experienced because of servomechanism failure. |
| Evaluate Years to Payback | NIST building lifecycle program | <1 year (typical 25MMbut/h boiler) | Payback of 2.4 years observed for natural gas operation (also associated with lower natural gas prices). For operation with oil payback is 2.5 months. |
| | | | |
| **Qualitative Performance Objectives** | | | |
| Ensure ease of installation and configuration | Ability of average service technician to configure and deploy successfully | a single service technician able to deploy at least as quickly as 'baseline' or 'SoA' | Positive feedback gathered during interviews with boiler installers and operators, both at Watervliet Arsenal and with Fireye customers. |

| Performance Objective | Metric | Pre-demonstration Success Criteria | Assessment summary |
|---|---|---|---|
| Ensure ease of use for boiler operator | Ability of average boiler operator to use interface effectively and achieve necessary daily operational changes | boiler operators understanding features and able to take action for all regularly occurring events | Boiler operators easily acquired knowledge of controller operation and interface, and were able to operate it and take action. |
| Ensure system maintainability | Number of service calls and parts replacements | Within expectations of typical operator | Because of the short demonstration time, maintenance was not performed on system, and it was not necessary. PPC4000 is easy to maintain based on feedback from Fireye customers. |

Each performance objective presented in Table 3 is described in detail as follows.

*Boiler Efficiency*

The computation of fuel to steam efficiency requires a characterization of steam quality. The boiler operates at a constant steam pressure of 135 – 140 psig, based on steam pressure measurements. During February – March 2011, steam temperature was not recorded, but was periodically noted from a visual meter. In order to verify steam quality and ensure that the correct enthalpy was used in calculations, temperature was added to the data set collected from October 2011 through March 2012. From steam tables, we could verify that the steam produced was always in saturation conditions.

A first evaluation of performance was conducted on 1$^{st}$ set data. Figure 51 reports a view of durations of all sample steady state conditions collected, while Figure 52 shows a comparison among fuel to steam efficiency between baseline and O2 trim operation. Results indicated a deterioration of performance with the introduction of O2 trim.

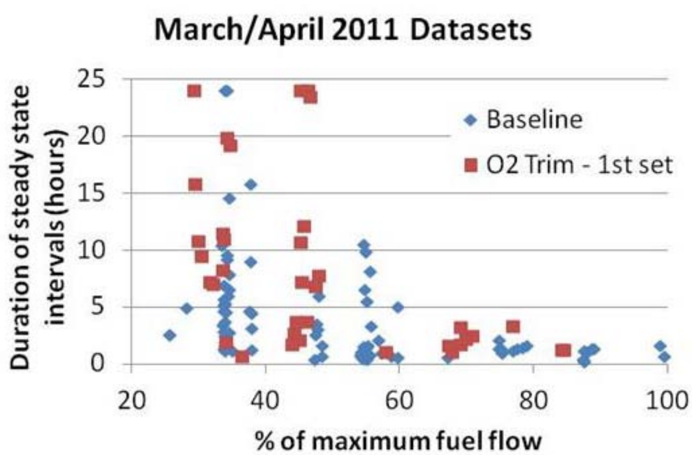



Figure 51 – First set of combustion control system data – spring 2011, sample duration

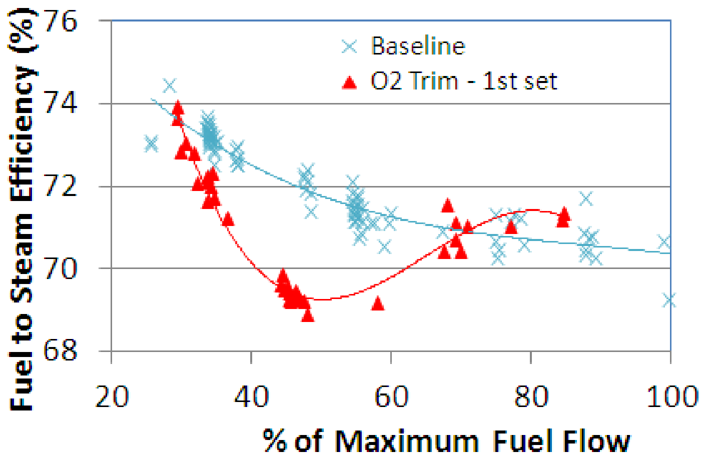


Figure 52 – First set of burner control system boiler efficiency comparisons – spring 2011

To understand the causes of recorded performance degradation, it is essential to verify the effect of upgrading the control system on those variables associated with modifications of the combustion process via changes to the fuel/air ratio, i.e. stack $O_2$ concentration and net exhaust temperature (Figure 53).

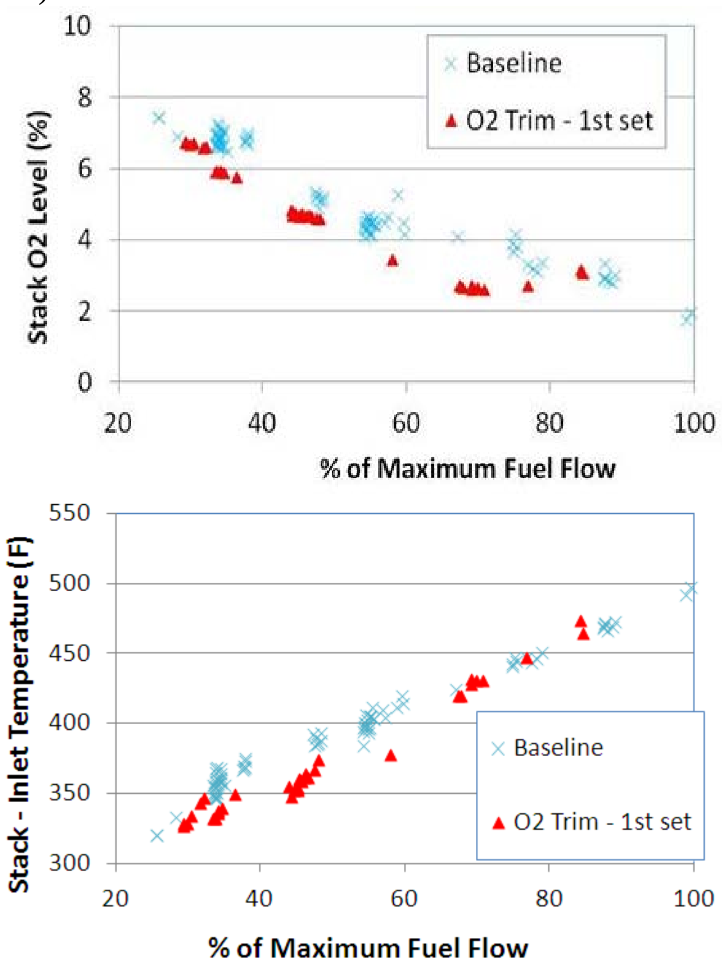


Figure 53 – Factors affecting boiler efficiency results for first comparison of results

Measurements indicate a reduction of oxygen concentrations across the firing range by using O2 trim, which is expected. In addition, net stack temperatures are lower for O2 trim, which seem to indicate effective heat transfer from the air side to the water side. This translates into a gain in combustion efficiency (see Figure 62) which however does not correspond to a measured fuel to steam efficiency gain. Results seem therefore to suggest that variations of other parameters contributing to fuel to steam efficiency or inaccuracy in measurements led to the results.

Indeed, many variables affect boiler efficiency, which are not related to the combustion process in the burner which the control system regulates. In particular, effectiveness of heat transfer from the air side to the water side is affected by phenomena local to the heat exchanger region, including evaporation of water to steam or local exhaust flow. In addition positioning of the flow steam meter and other exogenous factors may have contributed to biasing of results, which prompted a verification of all the instrumentation set up in August 2011.

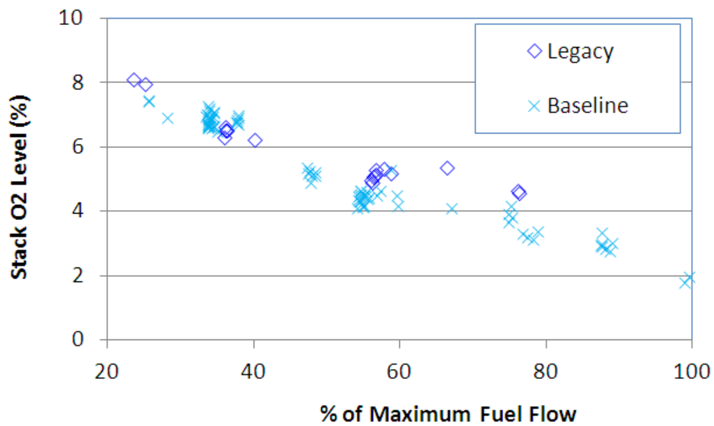



Figure 54 –Oxygen concentration for linkage baseline and PPC4000 legacy sets

Between October 2011 and March 2012, a series of tests with revised instrumentation in place were conducted. These include additional baseline measurements in “legacy” configuration with PPC4000 (see Section 5.4.4). For this set, the measured $O_2$ levels at the lower fuel flow rates were similar to those of the baseline profile (Figure 54). Moreover, assessment of CO/O2 trim control was included. Due to warm weather conditions during the winter of 2012, operation at high firing rates was not always possible due to reduced steam demand. Limited operation at higher firing rates was nevertheless possible. Figure 55 shows the duration of each steady state interval.

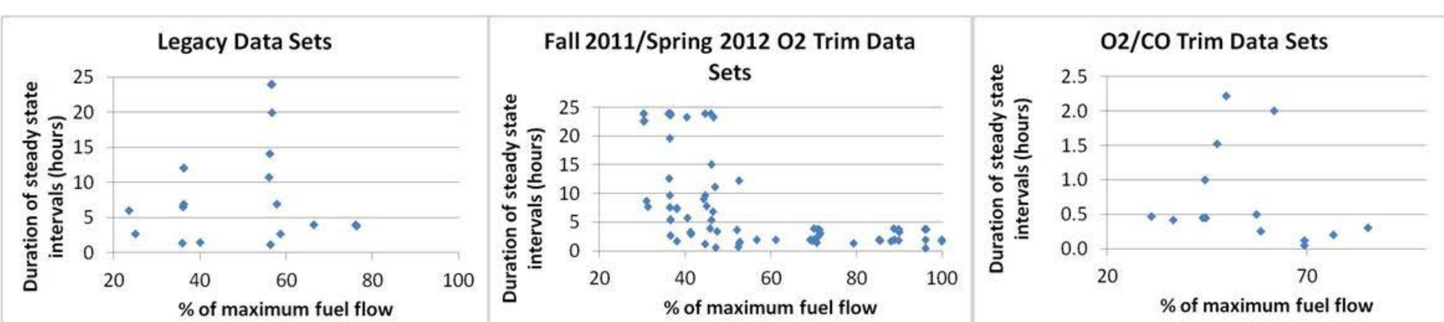



Figure 55 – Steady state intervals used in comparing all three burner control schemes

Data collected in O2 trim mode allowed to correct measurements taken in the spring of 2011. Figure 56 shows boiler efficiency as a function of both firing rate and stack $O_2$ concentration for each control mode. From the top plot, one can see that the efficiency improves for both O2 trim and CO/O2 trim control systems over legacy operation. This particular boiler efficiency profile is characterized by a drop in fuel to steam efficiency in the mid firing range, independent on the operation mode. This profile is not uncommon, as boiler manufacturers often guarantee an efficiency level for a specific fuel at a design, standard operating point [CIBO, 2003]. On the other hand, off-design efficiency changes with the boiler operating point. Efficiency of new, gas fired boilers range between 70 and 75%. The demonstration boiler lowest efficiency is observed at circa 55% of maximum fuel flow. Factors that may contribute to the specific efficiency curve shape include the heat exchangers geometry as well as change in shape, length and turbulence level of the burner flame at different firing rates and its orientation with respect to the water tubes closest to the flame. These changes affect both radiant and convective heat transfer to the water tubes carrying the process water/steam flow, as well as the nature of the water/steam two-phase flow in those tubes [Heselton, Chapter 9, 2005].

The plot in Figure 57 shows two trends. First, by upgrading the control system to O2 trim and then to CO/O2 trim allows operation at progressively lower oxygen concentrations. Operation at lower oxygen level translates in a benefit in terms of boiler efficiency when O2 trim is adopted across the firing range, but it's limited to the lower range of firing rates when CO/O2 trim is used, even if the boiler can be operated at oxygen concentration well below 2%. Ultimately, operating the boiler with CO/O2 trim shows improved performance ranging between 0.5% and 1.5% at lower firing rates.

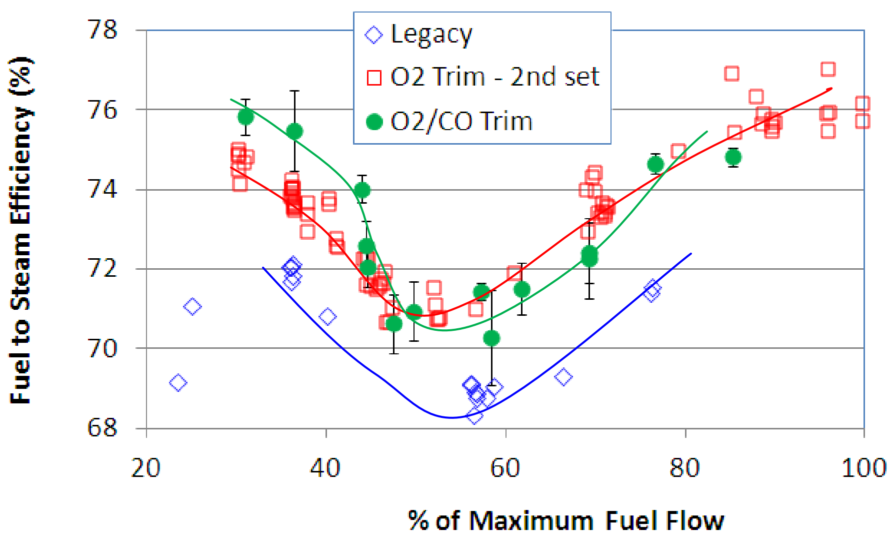



Figure 56 – 2nd data set: boiler efficiency comparisons with varying operating conditions

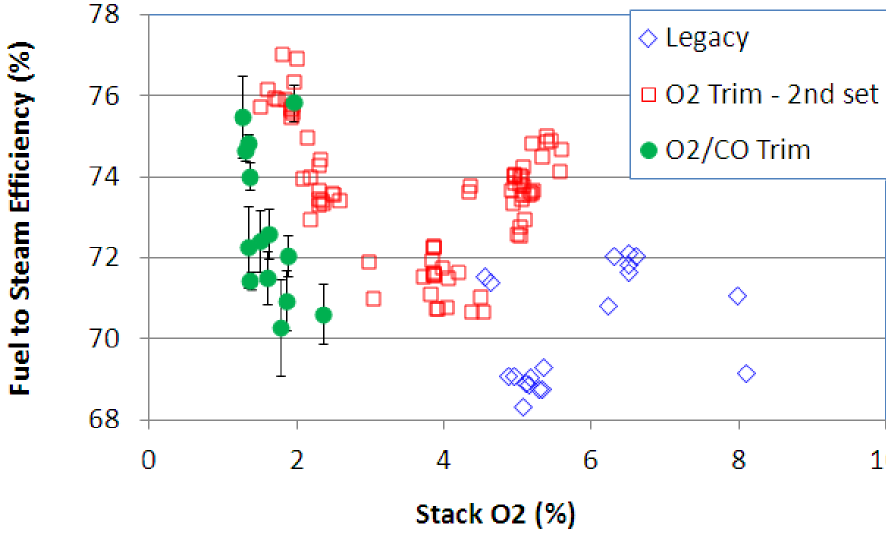


Figure 57 – 2nd data set: boiler efficiency comparisons with varying stack oxygen concentration

The reason why reductions in $O_2$ concentrations do not translate into larger efficiency gains could include the effect of several other uncontrollable factors on boiler performance. Such factors include changing weather conditions (temperature and humidity) and demand variations.

An additional test was conducted to reduce the impact of variation effects by manually changing the air servomechanism position to sweep through a range of fuel/air rates. The test was performed within hours. Five different firing rates were considered. For each, the air flow rate was reduced from its commissioned level while monitoring oxygen and carbon monoxide concentrations. $O_2$ concentrations of 1% were reached without formation of CO. Figure 58 illustrates the variation in fuel to steam efficiency in relation to oxygen concentrations. The test confirmed that reduction in oxygen concentrations has a positive impact on boiler efficiency, showing a gain of 1.5% for reduction of oxygen concentration from 4 to 2%. The curves also confirm that, as observed in Figure 56, lowest efficiency levels correspond to operation at 55% of maximum fuel flow.

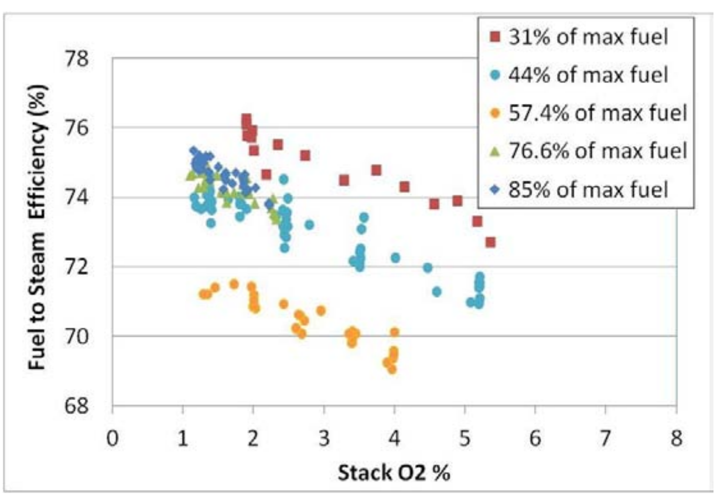


Figure 58 – The effect of stack $O_2$ reduction on fuel to steam efficiency

Performance quantification associated with No.2 oil operation was assessed. Operation with oil was possible only when requested by the local gas utility supplier, resulting in a limited data set. The plot of Figure 59 shows the number and duration of each steady state interval analyzed for oil-fired operation, and that of Figure 60 reports fuel to steam efficiency for changing fuel flow. Data was collected for baseline linkage and O2 trim controls, showing efficiency gains of 6-8%. Higher absolute efficiency levels were also observed. This is explained by the higher carbon to hydrogen ratio of oil vs. natural gas, so its combustion produces a higher ratio of carbon dioxide to water vapor. Carbon generates more radiant heat transfer to the water tubes and higher steam production. This observation is confirmed in [Heselton, 2005] reporting that watertube boilers extract 60% of fuel energy through radiant heat exchange. On the other hand, natural gas has a higher relative water vapor content in its exhaust and carries away a greater amount of latent heat than the carbon dioxide, resorting to increased heat losses. While oil fuel enables higher efficiency, it requires increased maintenance and has higher cost and emission levels.

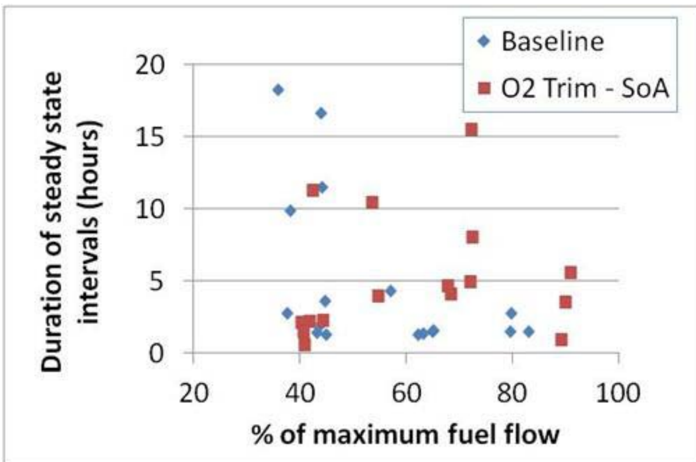



Figure 59 – Operation on No. 2 oil: sample duration

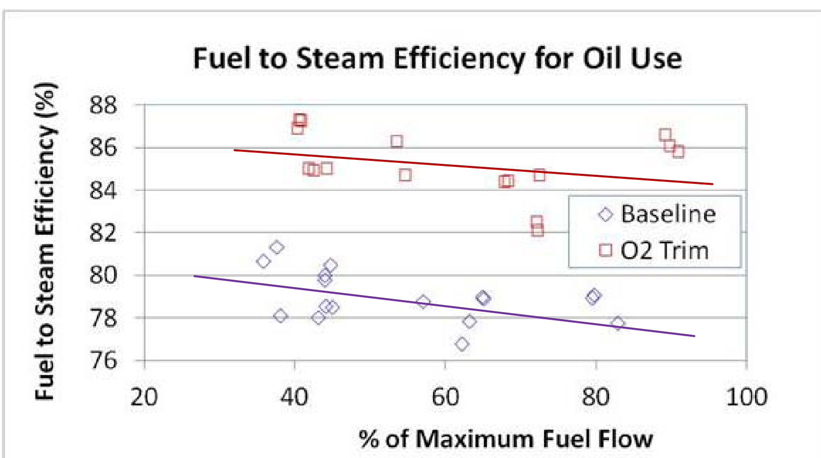



Figure 60 – Fuel to steam efficiency gains during boiler operation on No. 2 oil

*Emission reduction ($CO_2$)*

$CO_2$ emissions were calculated directly from fuel savings calculations, which depend on efficiency gains as well as utilization profiles (see Section 7.3.1 for details on calculations and

assumptions). Based on a prescribed base utilization profile, avoided $CO_2$ emissions are estimated as follows:

- For natural gas operation with O2 trim, $CO_2$ yearly emissions can be reduced by 288,000 lb (144 ton) on a 25 MMBtu/h boiler.
- For natural gas operation with CO/O2 trim, $CO_2$ yearly emissions can be reduced by 363,000 lb (181.5 ton) on a 25 MMBtu/h boiler.
- For No. 2 oil operation with O2 trim, $CO_2$ yearly emissions can be reduced by 784,000 lb (392 ton) on a 25 MMBtu/h boiler.

In general, $CO_2$ emissions avoided are on a percent basis equal to the amount of fuel saved. For the five reference heating profiles adopted in Section 7.3.1, $CO_2$ emissions savings are shown in the table below.

Table 17 – Emissions levels as calculated based on boiler utilization

| | | **Based on NG Fuel** | | | | | **Based on No. 2 Fuel Oil** | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | **NG Fuel Saved (MMB** | | **Reduced CO2 Emissions (lbs CO2/MMBTU)** | | | **No. 2 Fuel Oil Saved (MMBTU)** | **Reduced CO2 Emissions (lbs CO2/MMBTU)** |
| **Profile** | **Scenario** | **Total NG Fuel Baseline** | **O2 trim** | **CO/O2 trim** | **O2 trim** | **CO/O2 trim** | **Total No. 2 Fuel Oil Baseline** | **O2 trim** | **O2 trim** |
| 1 | Degree Day | 79,318 | 2,462 | 3,102 | **288,054** | **362,934** | 509,174 | 35,715 | **4,178,655** |
| 2 | Euro Efficiency | 79,515 | 2,481 | 3,003 | **290,277** | **351,351** | 518,457 | 36,472 | **4,267,224** |
| 3 | Low Loads | 43,795 | 1,248 | 1,949 | **146,016** | **228,033** | 277,759 | 19,062 | **2,230,254** |
| 4 | High Loads | 149,756 | 4,892 | 4,975 | **572,364** | **582,075** | 994,480 | 70,939 | **8,299,863** |
| 5 | NAVFAC | 80,852 | 2,424 | 3,164 | **283,608** | **370,188** | 520,499 | 36,464 | **4,266,288** |

*Combustion efficiency*

As explained in Section 3.1, combustion efficiency is a performance metric directly influenced by burner operation and flame stoichiometry, and therefore by the operation of the combustion controller. For this reason a more direct correlation between oxygen concentration reduction associated with technology adoption of O2 trim and CO/O2 trim control and gains in combustion efficiency is expected.

The combustion efficiency equation described in Section 3, and shown below, computes the amount of energy in the fuel that is transferred to steam by subtracting the heat content of the exhaust gases from the total energy in the fuel. While the heat content of the fuel can be easily determined by analysis, losses associated with the exhaust gases depend on the specifications of the fuel. In the equation three parameters ($K_1$, $K_2$, $K_3$) are calculated to determine the stack losses and account for the dry losses associated with $CO_2$, $N_2$ and excess $O_2$ and the wet losses due to water vapor.

$$\eta\ [\%] = 100\% - 20.9 \cdot K_{1g} \cdot T_{net} / [K_2 \cdot (20.9 - \%O_2)] - K_3 \cdot (1 + 0.001 \cdot T_{net})$$

Table 17 below contains the parameters used for natural gas and No. 2 oil to determine the constants used to calculate combustion efficiency. Petroleum-based average fuel properties have changed over the last decade, and both natural gas and fuel oil, which are blends of species that vary in time and geographic location, have variations in properties that impact both combustion

and fuel to steam efficiency. In all natural gas data sets, the specific heating value provided daily by Dominion Gas for Schenectady, NY was used for the specific day on which each test occurred in calculating fuel to steam efficiency. Over the last year of testing at Watervliet, the heating value of natural gas reported by Dominion ranged between 1023 and 1042 Btu/scf, averaging 1031 Btu/scf. The combustion efficiency calculations use the higher heating value, as specified in [ASME PTC 4-2008].

Table 18 – Fuel Properties and Combustion Parameters

| | Natural Gas | Fuel Oil No. 2 |
|---|---|---|
| Higher heating value (kJ/kg) | 52219 | 45241 |
| Lower heating value (kJ/kg) | 45806 | 42699 |
| % C in fuel | 72.1 | 86.5 |
| % H in fuel | 23.9 | 13.2 |
| K1g (based on HHV) | 0.3521 | 0.4876 |
| K1n (based on LHV) | 0.4014 | 0.5166 |
| K2 = maximum % CO2 | 11.8 | 15.6 |
| K3 | 9.99 | 6.3679 |

Figure 61 reports the combustion efficiency of the spring 2011 tests, and Figure 62 the fall-winter 2011-12 tests as a function of normalized fuel flow. From analysis of the earlier set, one could see that adoption of O2 trim control leads to about 1% improvement over baseline at low fuel flow, but drops off at high fuel flow rates. Referring back to the left plot in Figure 53 the stack $O_2$ concentration profile for both systems is similar, which has a direct correlation with combustion efficiency.

The plot in Figure 62 includes operational data for the CO/O2 trim control system. As anticipated, limited data were collected for this configuration. Combustion efficiency of the two systems is similar at high firing rates, although significantly better than the legacy configuration. At lower firing rates combustion efficiency is significantly higher, 1%-1.5% higher than levels recorded with O2 trim.

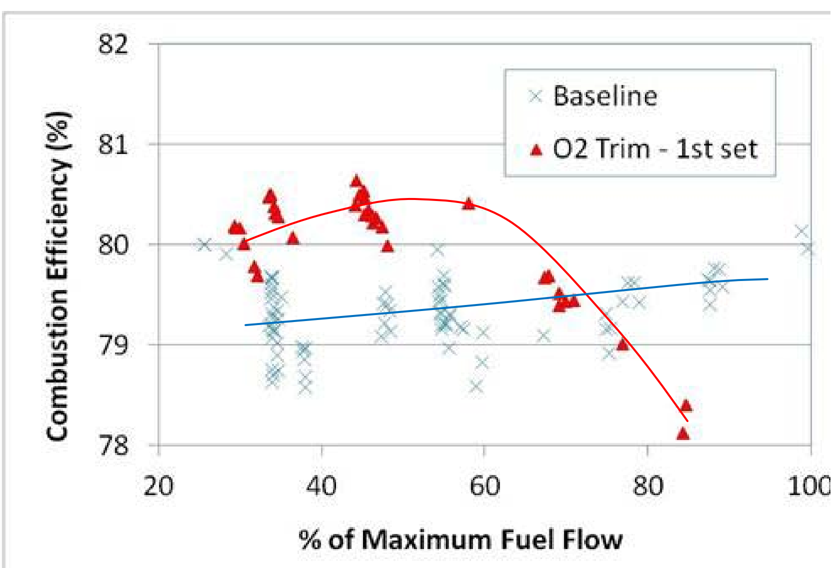



Figure 61 – Combustion efficiency for the 1st set of tests

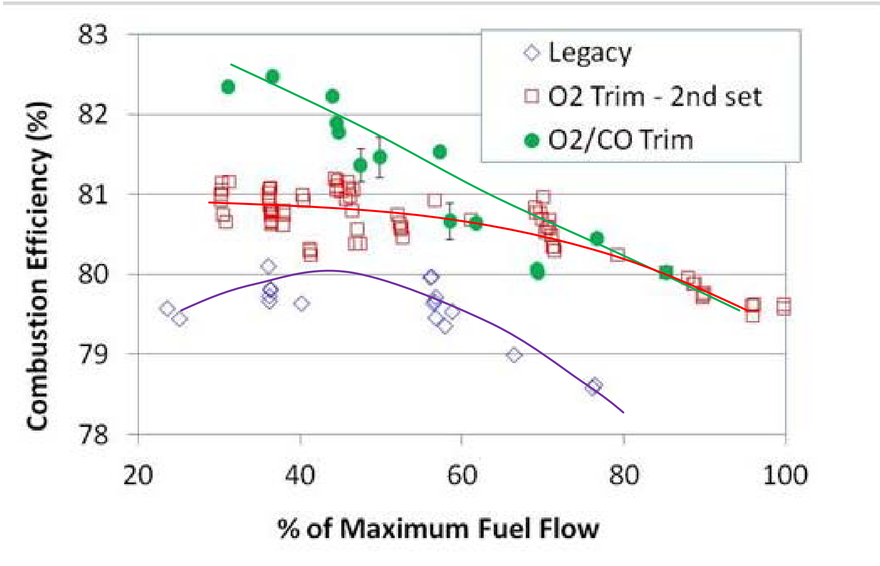


Figure 62 –Combustion efficiency for the 2nd set of tests

In Figure 63, the stack $O_2$ concentrations measures for all configurations are reported. Operation of the boiler at lower oxygen level has a direct impact on combustion efficiency.

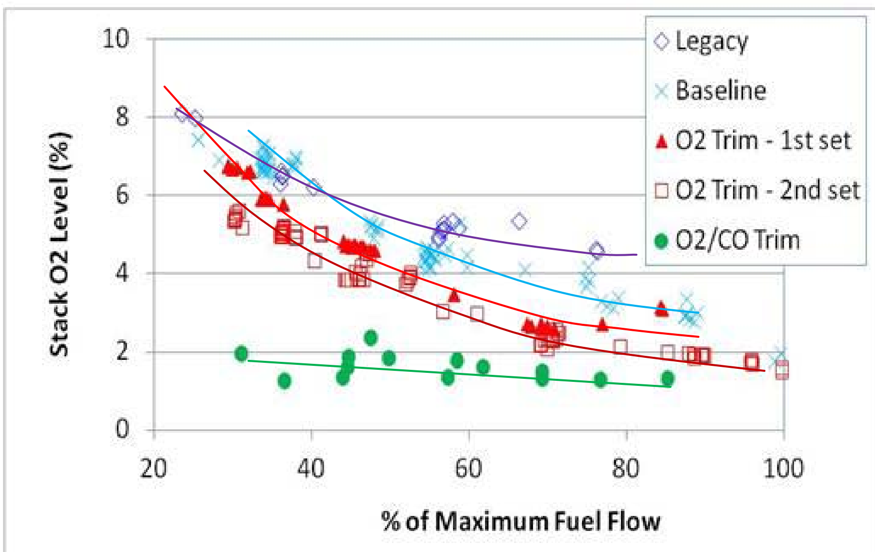


Figure 63 – Oxygen concentration variation with fuel flow

Similar to Figure 58, calculations of combustion efficiency in function of oxygen concentrations at different firing rates were conducted during short term tests aimed at minimizing long term variations of exogenous parameters. Figure 64 report such calculations: combustion efficiency increases with decreasing firing rates, and also increases with decreasing oxygen concentration, about 1.5% from 4% to 2%.

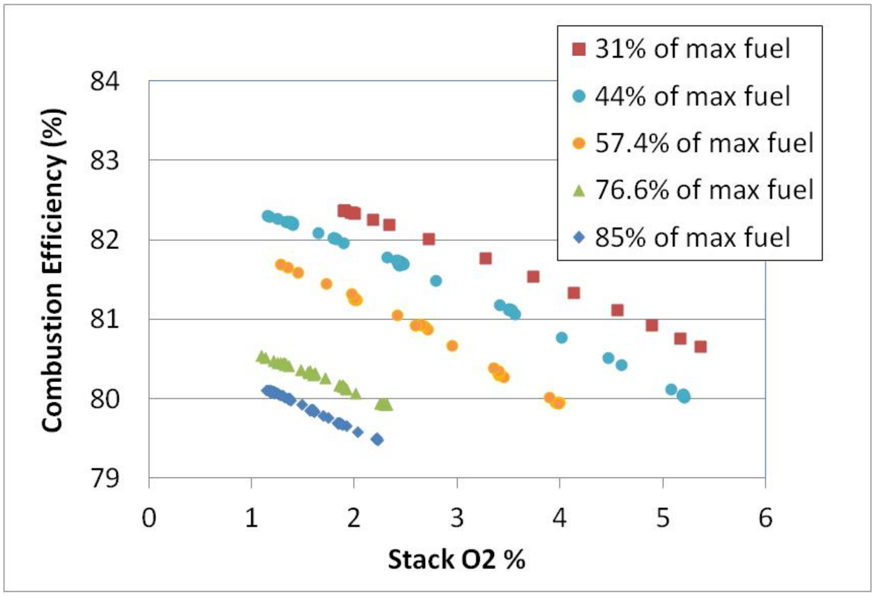


Figure 64 – Effect of stack oxygen reduction on combustion efficiency

Data relative to combustion efficiency for oil operation confirm the trends observed for natural gas (Figure 65 and Figure 66). Outlier points were observed for two steady state scenarios observed. Malfunctioning of the instrumentation is the likely cause.

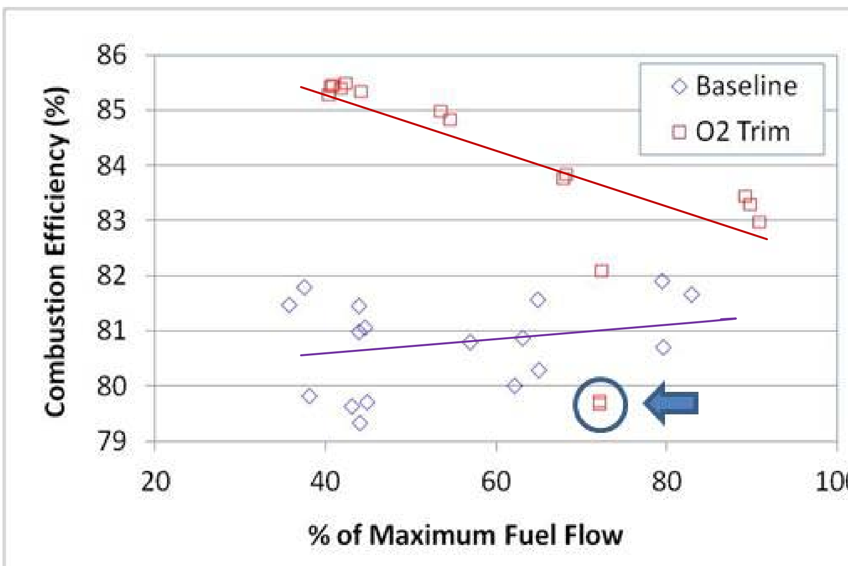


Figure 65 – Combustion efficiency comparisons of baseline and $O_2$ trim control using fuel oil

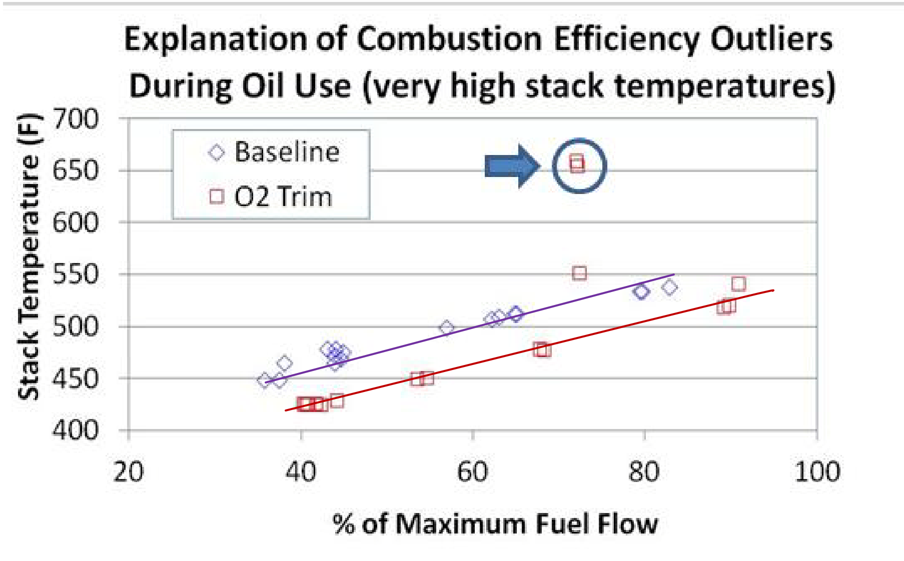



Figure 66 – Stack temperature comparisons of baseline and $O_2$ trim control using fuel oil

*CO and $NO_x$ emission limits*

During all tests at the demonstration site gas analysis data was recorded. Emissions measurements during tests in spring 2011 were however not fully captured because of limits with the gas sampling instrumentation. On the other hand, emissions measurements for all tests conducted between October 2011 and March 2012 were acquired, and averages, minimum and maximum values for both CO and $NO_x$ were tabulated (Figure 68). Operation with both SoA O2 trim and CO/O2 trim did not result in significantly higher CO concentration relative to baseline operation. Average levels were well within regulatory boundaries, while peak levels recorded were mostly relative to controller mistuning that was subsequently corrected. A variation of $NO_x$ levels with type of controller used was recorded, and is mostly associated with higher stack temperatures. However, $NO_x$ production variations associated with switching to a new control solution were limited and well below the target of 120 ppmv specified before the demonstration. It should be noted that $NO_x$ reduction would be mostly attainable by acting on the burner rather than on the fuel air ratio.

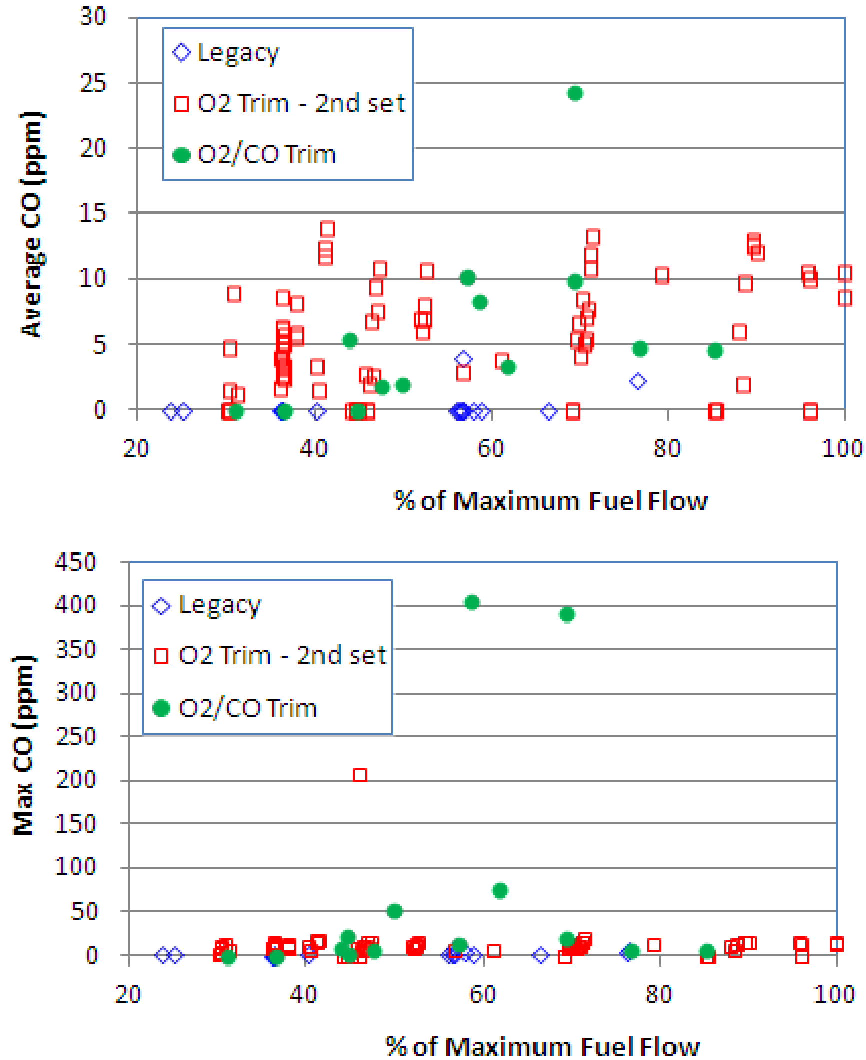



Figure 67 – CO emissions levels, average and maximum concentrations

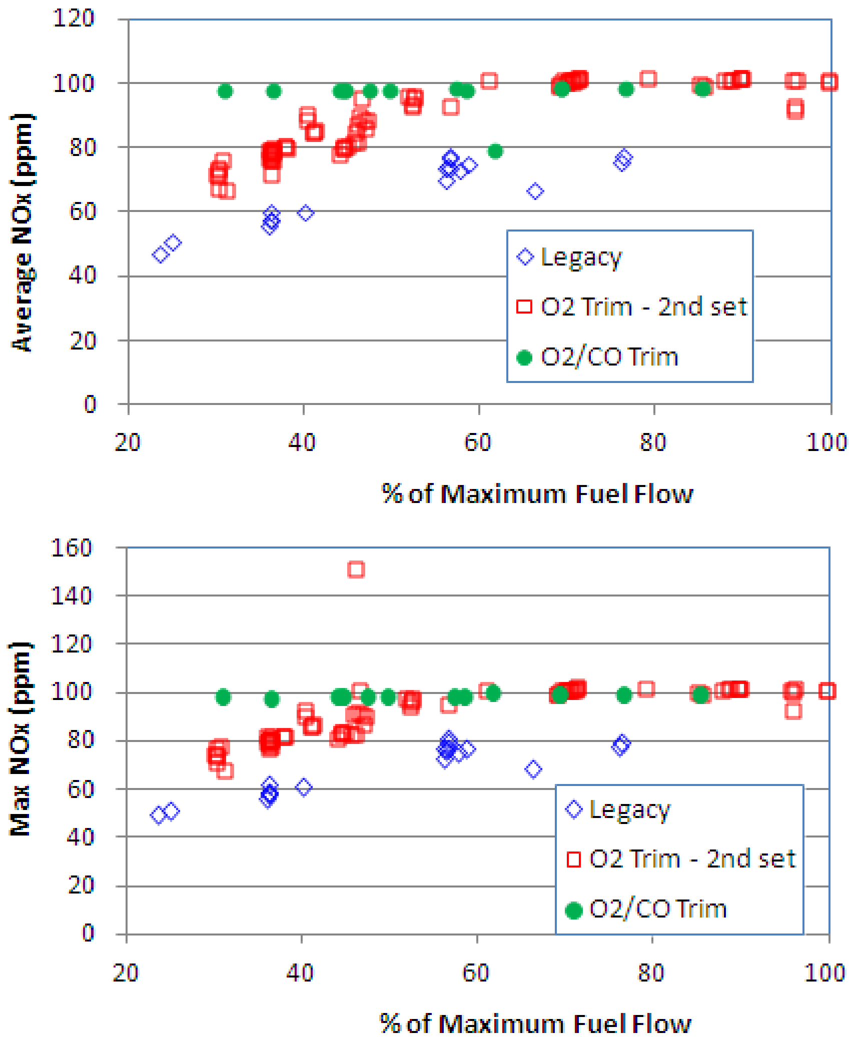



Figure 68 – $NO_x$ emissions levels, average and maximum concentrations

*Reduction of commissioning time*

Commissioning and re-commissioning times were not quantified directly via ad-hoc tests for the following reasons:

- As the boiler was already commissioned in baseline state when demonstration began, the recommissioning of the linkage executed at the end of the baseline demonstration took less than an hour. This activity was not reflective of an actual system commissioning performed at first installation.
- Commissioning with PPC4000 was performed within 2 hours as baseline points were initially used as reference. Therefore, commissioning activities were not reflective of typical commissioning times.

Boiler installers however noticed how the use of the PPC4000 interface for commissioning was easy to use, and greatly simplified the commissioning procedures. In similar installations,

customers of Fireye noted that the use of PPC4000 reduced commissioning times to 30% of a baseline commissioning activity.

*Boiler operating cost*
See Section 7 for a quantification of operating costs. On a percent basis, with the assumptions made in Section 7.3.1, annual operational savings are 3.6% over baseline, and 0.6% over SoA operational costs, for operation with natural gas. Operational cost improvement is 6.5% for SoA over baseline for operation with oil.

*Sensor reliability*
Sensor accuracy as measured in laboratory setting is discussed in Section 2.2.2. Requirements relative to calibration and stability are addressed in Section 5.5.1. Overall, the sensor technology adopted for control purposes showed good reliability and stability during the demonstration. Failures or malfunctioning were not experienced.

*Availability*
System downtime associated with the CO/O2 trim technology was experienced a single time during the execution of the demonstration, leading to a two hours downtime. While in O2 trim operation, one of the released product servomechanisms failed and had to be replaced. Failure was likely associated with servo installation procedures and the complexity associated with installation of the air servo to the air damper through a mechanical shaft, rather than the servomechanism itself. The servomechanism could be quickly replaced limiting the downtime to two hours. Overall, the target of >95% availability was attained.

*Payback*
See Section 7 for a quantification of investment performance metrics. The metric target was not attained for operation with natural gas, principally because of reduction of the price of natural gas (payback of 2.4 years). The target of <1 year payback was attained with oil with the SoA control (payback of 0.2 years).

*Ease of installation*
System installation is associated with the ease of setting up the PPC4000 product, whether in O2 trim or CO/O2 trim mode. Since Fireye released the product in 2010, feedback from new customers were collected as part of UTC's market feedback process. In the following, comments from installers and users are reported:

- From a distributor: "2-1/2 hours to set up and have a boiler on-line in auto-mode."
- From a burner OEM: "With the system we set up to use the SD card [a feature of PPC4000] to upload info, they are able to get some similar burners through their test pit in 10 minutes."
- From a distributor: "The system is significantly easier to program and operate. The complexity has been reduced instead of 25 options there are now only 7 which is sufficient for smooth operation."

Joe Firlet, the responsible for boiler maintenance and upgrade at Watervliet Arsenal commented on PPC4000 as follows, noting pros and cons of the new digital technology.

Pros:

- Nice package, easy to use;
- Expandable;
- Works well with the Fireye E100 BMS system (the existing flame safeguard system);
- Small in size yet powerful.

Cons:

- Display is small cannot see information from far away (A larger touch screen is going to be released, but was not yet available at the demonstration site);
- Needs markings on the actuators so we can visually see how much open/closed it is;
- Needs to work in automatic with a plant master (the feature is available but was not implemented at Watervliet).

*Ease of use for operator*

Comments from Fireye's customer base were also captured;

- From a customer: "The installation went smooth and we have not had one issue since the initial startup. We are very happy with the control;"
- From a customer: "…people were extremely pleased. I mean really ecstatic! The modulation PID was working so well they had excellent operation on their feed water which in and of itself will show less wear and tear on the feed water pump. Steam pressure was a perfect circle around the chart recorder."

*Maintainability*

See Section 7 for comments on maintenance cost estimates. During the execution of the demonstration, maintenance problems were not encountered.

# 7. COST ASSESSMENT

As costs and benefits of introduction of new boiler control technology depend largely on the specific application, geographic location, type and cost of fuel, the analysis that follows can only provide estimates based on a number of assumptions. Whenever available, data specific to the demonstration boiler and its geographic location were used. The cost and benefit model was implemented in an excel spreadsheet which can be modified to make economic benefit assessments for a specific boiler and sites.

## 7.1 COST MODEL

The expected life cycle costs the NIST developed 'Buildings Life-Cycle Cost Program' (V5.3) was used, with specific reference to DoD ECIP projects. The following cost elements were collected by Fireye based on prices available for the current SoA control system (PPC4000 with O2 trim) applicable to the demonstration boiler. Not all cost elements used for the model were based on tracked data obtained during the demonstration for the following reasons:

- Often, costs incurred were associated to the development of prototypes, which would be substantially different than costs of production of a finished product.
- Prices to customer need to be used to determine benefits associated with the investment in the new combustion control technology. Actual prices of new technology elements would depend on the future pricing strategies for the finished product.

The elements summarized in Table 19 were calculated or determined for calculation of the cost model.

Table 19 – Fireye PPC4000 quotation for 25 MMBtu/h boiler

| Cost Factor | Data Tracked During the Demonstration |
|---|---|
| **(1) Hardware capital costs** | • Actual pricing of the PPC4000 $O_2$ trim systems were provided by Fireye. The additional costs associated with the $CO/O_2$ trim technology are associated with the $CO/O_2$ sensing unit. A final price for the unit is not available and a cost range was used. |
| **(2) Installation costs** | • Labor and materials other than hardware required to install system hardware were provided by Fireye based on experience from similar sites.<br>• Costs associated with regulatory compliance and facility utility interruptions. Not tracked. As updates to the new controller are implemented during scheduled downtime, there is no additional opportunity cost associated with installation. |

| Cost Factor | Data Tracked During the Demonstration |
|---|---|
| **(3) Consumables** | • Costs for consumables used during the demonstration were not tracked specifically and considered part of the maintenance costs estimates.<br>• Sensor life outlasted the demonstration period and was considered under ‘Maintenance’. |
| **(4) Facility operational costs** | • Fuel (gas, oil); electric power, water. Cost of gas and oil used were based on current EIA published costs and information provided by Watervliet Arsenal’s Energy Manager.<br>• Costs of fuel saved were based on actual measured boiler performance and estimates for utilization based on realistic scenarios. |
| **(5) Maintenance** | • Estimates of differential maintenance costs vs. baseline were provided by Fireye. Such costs are associated with replacement costs of components and recalibration labor costs. |
| **(6) Hardware lifetime** | • It was confirmed that lifetime of the systems is much longer than the duration of the demonstration. |
| **(7) Operator training** | • Training costs are integrated into overall installation costs estimated by Fireye. |

The following briefly explains each of the cost elements in Table 19, the data and assumptions made.

1. **Hardware capital costs**: The upgrade cost from baseline to SoA as applicable to the demonstration boiler was provided by Fireye based on an actual price quotation. The quote is reported in Table 20.

Table 20 - Cost evaluation factors and source

| Products | Item | Quan | P/N | Description | Price Ea. | Total |
|---|---|---|---|---|---|---|
| | | | | **Basic System** | | |
|  | 1 | 1 | PPC4000 | UL Approved Parallel positioning, Controller. Operates with up to ten (10) FX Modbus Servo-motor outputs. | $900.00 | $900.00 |
|  | 2 | 1 | NXD410 | 15 Key, 4 Line, 40 Character Full text Display with Modbus, Backlit LCD for PPC4000. | $504.00 | $504.00 |
|  | 3 | 1 | PXMS-xxx (range) | Steam Pressure Sensor | $670.00 | $670.00 |
|  | 4 | 1 | 59-562-2 | Display Connection cable 10 feet | $61.20 | $61.20 |
| | | | | **Servo Options** | | |

| Products | Item | Quan | P/N | Description | Price Ea. | Total |
|---|---|---|---|---|---|---|
|  | 5 | 2 | FX04 | 4 wire Modbus Servo-motor, 3 ft lbs., 4Nm, 50/60 Hz, 24 VDC. FUEL SERVOS | $319.80 | $639.60 |
| | 6 | 1 | FX20 | 4 wire Modbus Servo-motor, 15 ft lbs., 204Nm, 50/60 Hz, 24 VDC. AIR SERVO | $589.80 | $589.80 |
|  | 7 | 1 | NXCBGO3FT | Retrofit Kit brackets and Couplings, Gas Fittings/ Oil Cam | $1,020.00 | $1,020.00 |
| | | | | **Total for Base Systems** | | **$4,384.60** |
| | | | | - | - | |
| | | | | **O2 trim Option** | | |
| | 8 | 1 | 35-318-2 | O2 Probe Mounting flange | $171.60 | $171.60 |
|  | 9 | 1 | NXCESO2-8 | O2 probe assembly (for flues 300mm to 1000mm). | $1,908.00 | $1,908.00 |
| | 10 | 1 | 129-189 | Mounting Flange blank cover | $127.80 | $127.80 |
| | | | | **Total for O2 trim Options** | | **$2,207.40** |
| | | | | **Field Options** | | |
| | 11 | 1 | 253-WD-2 | Wiring Diagrams and Drawings * | $400.00 | $400.00 |
| | 12 | 1 | 59-565 | Belden 9940 wire 1200 ft | $1,080.00 | $1,080.00 |
| | | | | **Total Field Options** | add | **$1,480.00** |
| | | | | *** Note 1 set Drawings per site** | | - |
| | | | | | | - |
| | 13 | 1 | Install/ Commission | **Installation & Commissioning Works Complete System** | $16,000.00 | **$16,000.00** |

| | |
|---|---|
| **GRAND TOTAL** | **$24,072.00** |

For the upgrade to the $CO/O_2$ operation, the necessary gas sensing package is today commercially not available – although most of its components are COTS. While costs for construction of the sensor device prototype are available, Fireye considered that the final product would certainly undergo design modifications. For this reason, costs for prototype construction cannot be used in the analysis. In addition, as a pricing strategy is not yet defined, a range of prices for the new sensor device was used, i.e. $5,000-$25,000. To evaluate the total system cost, this cost item was added and that of the $O_2$ probe subtracted. As the analysis includes results for a larger size boiler (100 MMBtu/h) the cost for this large unit was updated to account for larger fuel and air servos. An increment of $5,000 was estimated by Fireye to include labor and equipment.

2. **Installation costs**: Planning, physical installation, configuration and initial commissioning efforts of a technician were included in the estimate provided by Fireye as reported in Table 20.

3. **Consumables**: Consumable components include replacement parts for the $O_2$ probe of the O2 trim controller, i.e. a sensor cartridge and for the sensor box of the CO/O2 trim system,

i.e. the scrubber used for elimination of nitrogen and sulfur oxides. Costs of these components were included in the estimate of recurring annual maintenance costs.

4. **Facility operational costs**: Costs associated with the operation of a boiler system are fuel and electric power costs, as well as personnel cost to operate the facility. The introduction of the new combustion efficiency controls used for this demonstration (both O2 trim and CO/O2 trim) has a beneficial effect on fuel cost savings, while all other operational costs are unchanged. It should be noted that these new electronic control systems can provide electric power savings when used with a variable speed drive modulating the air fan speed. Such configuration was not tested in this demonstration and therefore electric power savings could not be evaluated and quantified. In conclusion, operational cost savings were calculated in terms of fuel cost savings only for both upgrades to O2 trim (SoA) and CO/O2 trim technology. Fuel costs savings were quantified by adopting a model which requires the following information:

- *Boiler fuel to steam efficiency* for baseline, O2 trim, and CO/O2 trim configurations across the firing range of the boiler. This information was obtained by using actual measurement data collected during the demonstration phase. Average values were extracted for discrete part load conditions (20%, 30%, 40%, 60%, 80%, and 100% of steam output) resulting in the efficiency table below relative to natural gas operation:

Table 21 – Efficiency table for natural gas

| % Output | Fuel to Steam Efficiency | | |
|---|---|---|---|
| | Legacy | O2 Trim | CO/O2 Trim |
| 20% | 72.7% | 74.8% | 76.2% |
| 30% | 72.0% | 74.0% | 75.7% |
| 40% | 69.0% | 71.0% | 71.7% |
| 60% | 70.7% | 73.3% | 73.3% |
| 80% | 73.3% | 75.7% | 75.7% |
| 100% | 74.0% | 76.3% | 76.3% |

Operation with No. 2 oil was quantified only for baseline legacy as well as O2 trim, but not for the CO/O2 trim technology. Efficiency levels at part load conditions are reported below.

Table 22 – Efficiency table for No. 2 oil

| % Output | Fuel to Steam Efficiency | |
|---|---|---|
| | Legacy | O2 Trim |
| 20% | 82.0% | 88.0% |
| 30% | 81.0% | 87.0% |
| 40% | 80.0% | 86.0% |
| 60% | 78.0% | 84.0% |
| 80% | 78.0% | 84.0% |
| 100% | 82.0% | 88.0% |

- *Boiler utilization factors*, expressed in terms of total annual hour of utilization and percent of operation time at each discrete part load condition. The utilization data of the current boiler was not used, as it is operated as backup boiler. Instead, a set of 5 utilization curves were used to reflect different typical uses of a boiler. The total hours of operation was computed based on the quantification of the number of days in a year with positive heating

degree days for Albany, NY. Weather data for a three year period before March 2012 was used and averaged to extract yearly data. The utilization profiles of Table 23 were used.

Table 23 – Utilization profiles

| Profile | Hours of operation | 10% | 20% | 30% | 40% | 60% | 80% | 100% |
|---|---|---|---|---|---|---|---|---|
| 1 | 6352 | 20.0% | 15.5% | 16.8% | 23.8% | 18.8% | 5.0% | 0.1% |
| 2 | 6352 | 25% | 25% | 10% | 10% | 15% | 15% | 0% |
| 3 | 6352 | 40% | 40% | 10% | 10% | 0% | 0% | 0% |
| 4 | 6352 | 0% | 0% | 0% | 10% | 40% | 50% | 0% |
| 5 | 6352 | 15% | 15% | 25% | 25% | 10% | 10% | 0% |

The profiles were computed as follows: Profile 1 was obtained by calculating a day's boiler load as proportional to the average degree day, with 100% assigned to the highest overall degree day value. Frequencies were calculated for load intervals centered at the desired %Load value. Profile 2 is based on utilization factors prescribed by the ESEER standard European efficiency calculation for boilers [CIBSE, 2008]. Profile 3 and 4 are low and high load utilization profiles respectively, whereas Profile 5 is derived from discussions with Naval Facilities Engineering Command (NAVFAC) boiler operation experts.

- *Fuel type and cost*. This analysis considers natural gas as well as No. 2 oil as fuels. For natural gas, the wholesale cost ~\$3/MMBtu was obtained from the EIA database and an additional delivery cost of \$2.5/MMBtu was added. A rate of \$5.5MMBtu/h is indeed what Watervliet Arsenal is paying for natural gas as of March 2012. Sensitivity of economic performance indicators to fuel costs was performed by considering prices in the \$1-10MMBtu/h range. For No. 2 oil, a price of \$4/gal was considered, which is close to its March 2012 price. Fuel cost savings were calculated by subtracting the annual cost of fuel associated with new technology adoption to the annual cost of fuel of baseline, based on the data and assumptions above. Calculations are reported below:

$$Fuel\ Cost\ Savings = Price\ of\ \ NG \cdot Fuel\ Saved$$

$$Fuel\ Saved\ = Baseline\ Fuel\ Used - New\ Tech\ Fuel\ Used$$

$$Fuel\ Used = \sum_{Load\ Levels} \frac{Max\ Load \cdot Load\ Level}{Efficiency\ @\ Load\ Level} Hours\ @\ Load\ Level$$

5. **Maintenance**: Maintenance costs were not tracked during the demonstration, and estimates of costs were provided by using qualitative information and making realistic costs assumptions. The following considerations were made:
   - Costs for maintenance of baseline systems are higher than those of an electronic positioning control system, as the linkage requires more frequent readjustment and recalibration.
   - Trim controllers have replacement parts that need to be periodically substituted to allow the correct functioning of the system. Instrument recalibration can add to the cost of maintaining such systems.

- For O2 trim system, Fireye does not consider a significant increase in need for maintenance. Rather, it is an easier system to operate than baseline. CO/O2 trim maintenance requirements have not been quantified with precision. However, the CO/O2 sensor system performed well during the demonstration.

For the above reasons, a conservative estimate for maintenance costs was made for the O2 trim system ($1,000/year) and the CO/O2 trim system ($1,500/year).

6. **Hardware lifetime**: This metric was not tracked during the demonstration. Based on information on how positioning and trim systems perform in the field, lifetime is much longer than 10 years.

7. **Operator training**: Training costs have been included as part of the installation cost estimates. The PPC4000 product has been praised in the field for its ease of use with programming, calibration, and operation. Personnel at Watervliet Arsenal did not raise concerns associated with the operation of the system.

## 7.2 COST DRIVERS

When selecting the technology for future implementation on a boiler, there are a number of factors that would influence system cost as well as actual achievable savings and ultimately the value proposition of the investment. Such cost drivers are:

1. *Boiler size*: Cost of the system would change with boiler size, driven by the size of the servomechanisms for air and fuel modulation. As boiler capacity increases, servos capable of higher torque level have to be employed, adding to system cost.
2. *Boiler utilization*: Attainable fuel savings will depend on the utilization factor of the boiler and the load profile, as fuel to steam efficiency changes with boiler load. In addition, the least time the boiler is in operation, the smallest will be the savings. Utilization will depend in demand for heating which will be related to geographical location and typical weather conditions for that location. As climate modifications and trending towards weather extremes is experienced, utilization factors may change drastically.
3. *Boiler heat transfer effectiveness*: While the CO/O2 trim controller will operate to achieve always the highest level of combustion efficiency, how that relates to overall fuel savings will depend on the effectiveness of the boiler to transfer additional heat to the water or vapor.
4. *Type and cost of fuel*: The type and cost of fuel will influence the total dollar savings that the technology can provide.
5. *Local cost of manpower*: Changes in the installation and periodic maintenance costs could occur depending on prevailing wages in the particular U.S. state where the installation occurs.

## 7.3 COST ANALYSIS AND COMPARISON

Estimates of the costs for application of the state of the art and new technology in a realistic scenario as compared to the baseline are listed in the following. Data already reported in Section 7.1 will be summarized. In order to perform a full life cycle analysis associated with the adoption of state of the art and the new technology, the following was assumed:

- Weather conditions and boiler utilization typical of the Albany, NY area was considered for the analysis. 5 different utilization scenarios were considered as described in Section 7.1, which could be also applicable to different climatic conditions. The utilization scenarios also include extreme conditions to provide a range for the cost assessment.
- All assumptions for calculation of the elements of the cost model illustrated in the same section were adopted.
- Life cycle analysis adherent to the DoD ECIP guidelines was performed[3]. Consequently, all prescribed parameters for 2012 were utilized, including the discount rate (3%), the inflation rate (0.9%), prescribed annual fuel cost variations, the absence of final salvage value of the system and terminal value of the investment.
- The analysis was performed for 10 years life of the equipment.

### 7.3.1 Energy Cost Savings

By applying the cost model, energy savings in terms of total amount of natural gas saved as well as its associated cost were estimated for the five different utilization profiles. Detailed calculations relative to profile #1 are reported (for 25 MMBtu/h boiler size), together with a summary relative to all profiles.

Table 24 – Detailed energy cost savings estimation for a 25 MMBtu/h boiler, profile #1

| Maximum capacity | 25 MMbtu/hr | Profile | | 1 | | | | |
|---|---|---|---|---|---|---|---|---|
| **Operation** | **10%** | **20%** | **30%** | **40%** | **60%** | **80%** | **100%** | **TOTAL** |
| Heating load (MMbtu/hr) | 2.5 | 5 | 7.5 | 10 | 15 | 20 | 25 | |
| Hours during heating season | 1272 | 984 | 1064 | 1512 | 1192 | 320 | 8 | |
| Cycling (20% equivalent hours) | 60% | 763 | | | | | | |
| Hours of operation | | 1747 | 1064 | 1512 | 1192 | 320 | 8 | 6352 |
| Overall utilization | | | | | | | | 35.5% |
| **Fuel utilization (MMbtu)** | | | | | | | | |
| Fuel required: baseline | | 6.88 | 10.42 | 14.49 | 21.23 | 27.27 | 33.78 | 79317.82 |
| Fuel required: O2trim | | 6.68 | 10.14 | 14.08 | 20.45 | 26.43 | 32.75 | 76855.48 |
| Fuel required CO/O2trim | | 6.56 | 9.91 | 13.95 | 20.45 | 26.43 | 32.75 | 76215.49 |
| **Fuel savings (MMbtu)** | | | | | | | | |
| Fuel Saved: O2 trim | | 0.20 | 0.28 | 0.41 | 0.77 | 0.84 | 1.03 | 2462.35 |
| % Fuel Saved: O2 trim | | 2.90% | 2.70% | 2.82% | 3.64% | 3.08% | 3.06% | 3.10% |
| Fuel Saved: CO/O2 trim | | 0.32 | 0.50 | 0.54 | 0.77 | 0.84 | 1.03 | 3102.33 |
| % Fuel Saved: CO/O2 trim | | 4.60% | 4.85% | 3.72% | 3.64% | 3.08% | 3.06% | 3.91% |
| lb of CO2 - reduction | | | | | | | | 288,341<br>363,283 |
| **Cost savings** | | | | | | | | |
| Cost of fuel ($/Mmbtu) | | | | | | | | 5.5 |
| O2 trim | | | | | | | | $ 13,543 |
| CO/O2 trim | | | | | | | | $ 17,063 |

Table 25 – Estimated annual energy cost savings for all 5 profiles (25 MMBtu/h)

| | Total Fuel | Fuel Saved (MMbtu) | | % Fuel Saved | | $ Saved | | |
|---|---|---|---|---|---|---|---|---|
| Profile | Baseline | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim | |
| 1 | 79,318 | 2,462 | 3,102 | 3.10% | 3.91% | $ 13,543 | $ 17,063 | Degree day |
| 2 | 79,515 | 2,481 | 3,003 | 3.12% | 3.78% | $ 13,646 | $ 16,518 | Euro efficiency |
| 3 | 43,795 | 1,248 | 1,949 | 2.85% | 4.45% | $ 6,864 | $ 10,717 | Low loads |
| 4 | 149,756 | 4,892 | 4,975 | 3.27% | 3.32% | $ 26,903 | $ 27,361 | High loads |
| 5 | 80,852 | 2,424 | 3,164 | 3.00% | 3.91% | $ 13,330 | $ 17,404 | NAVFAC |

[3] According to the Office of Management and Budget (OMB) Circular A-94 or information from Handbook 135, the Life-Cycle Costing Manual for the Federal Energy Management Program (FEMP) and its annual supplement. Parameters available in NIST's BLCC tool.

As annual fuel cost savings are highly sensitive to the cost of natural gas, a sensitivity analysis was performed to help quantify the effect of price variation on overall investment performance. Sensitivity with changing number of operation hours helps to illustrate variations with geographical operation, as a boiler would operate longer in a colder climate than a hotter one. In addition, utilization would depend on the number and use of boilers available in a multi-boiler power plant.

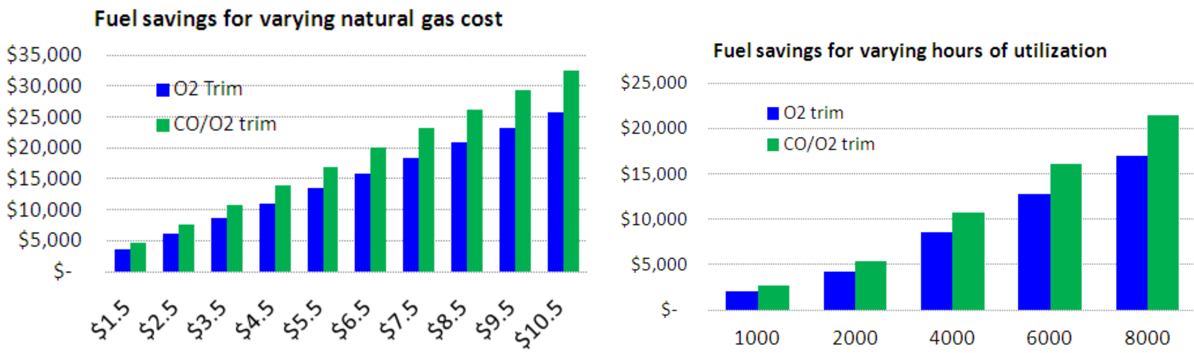



Figure 69 – Sensitivity to natural gas price variation and boiler yearly hours of utilization of annual fuel savings (25 MMBtu/h)

The analysis can be repeated for a larger size boiler, i.e. $100 MMBtu/h by means of scaling.

Table 26 – Estimated annual energy cost savings for all 5 profiles (100 MMBtu/h)

| | Total Fuel | Fuel Saved (MMbtu) | | % Fuel Saved | | $ Saved | | |
|---|---|---|---|---|---|---|---|---|
| Profile | Baseline | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim | |
| 1 | 317,271 | 9,849 | 12,409 | 3.10% | 3.91% | $ 54,172 | $ 68,251 | Degree day |
| 2 | 318,060 | 9,924 | 12,013 | 3.12% | 3.78% | $ 54,584 | $ 66,072 | Euro efficiency |
| 3 | 175,178 | 4,992 | 7,794 | 2.85% | 4.45% | $ 27,457 | $ 42,868 | Low loads |
| 4 | 599,024 | 19,566 | 19,899 | 3.27% | 3.32% | $ 107,614 | $ 109,445 | High loads |
| 5 | 323,409 | 9,694 | 12,658 | 3.00% | 3.91% | $ 53,319 | $ 69,618 | NAVFAC |

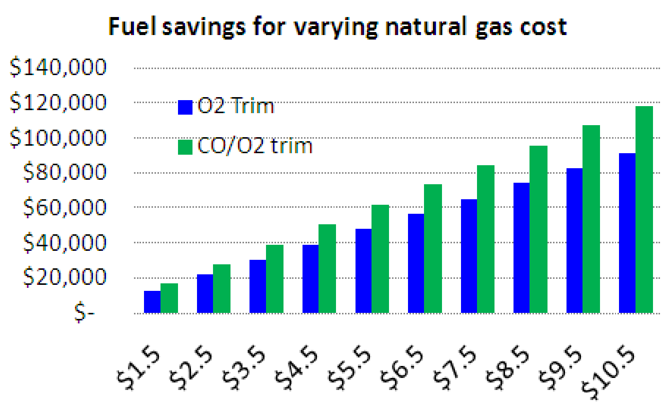



Figure 70 – Sensitivity to natural gas price variation of annual fuel savings (100 MMBtu/h)

It should be noted that fuel savings results are consistent for profiles 1, 2, and 5. Results for profiles 3 and 4 should be considered as applicable for extreme utilization of the boiler.

Performance of the boiler operating with No. 2 oil is estimated in the tables and charts below. As efficiency gains and cost of fuel are higher, achievable yearly energy savings are correspondingly higher.

Table 27 – Estimated annual energy cost savings for all 5 profiles (25 MMBtu/h, oil)

| Profile | Total Fuel Baseline | Fuel Saved (MMbtu) O2 trim | % Fuel Saved O2 trim | $ Saved O2 trim | |
|---|---|---|---|---|---|
| 1 | 509,174 | 35,715 | 7.01% | $ 142,858 | Degree day |
| 2 | 518,457 | 36,472 | 7.03% | $ 145,887 | Euro efficiency |
| 3 | 277,759 | 19,062 | 6.86% | $ 76,247 | Low loads |
| 4 | 994,480 | 70,939 | 7.13% | $ 283,758 | High loads |
| 5 | 520,499 | 36,464 | 7.01% | $ 145,855 | NAVFAC |

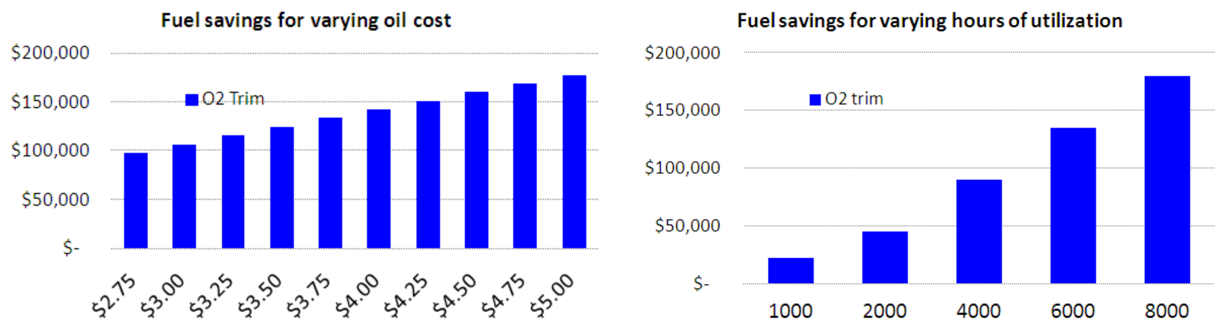


Figure 71 – Sensitivity to oil price variation of annual fuel savings (25 MMBtu/h)

### 7.3.2 Value of Technology Investment

For quantification of economic benefits associated with the investment in new control technology, whether SoA of new, a cash flow analysis considering all assumptions made in previous sections and calculated data was performed for natural gas fired boilers. Based on the analysis, variations were calculated according to:

- Boiler size (25 MMBtu/h or 100 MMBtu/h)
- Utilization profile
- Annual hours of boiler operation
- Cost of natural gas fuel
- First cost of the CO/O2 probe (the most uncertain fixed cost factor)

For a 25 MMBtu/h boiler with utilization profile #1, $5.5/MMBtu cost of fuel, and assumed cost for the CO/O2 probe of $15,000, a cash flow analysis was performed as reported in the tables below for state of the art O2 trim and new CO/O2 trim technology.

Table 28 – Base cash flow analysis, O2 trim technology

| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Investment | $ (24,072) | | | | | | | | | | $ (24,072) |
| Energy Price Variation | | -3.19% | -4.07% | -1.26% | 0.35% | 0.58% | 0.80% | 1.25% | 1.46% | 1.33% | |
| Savings | $ 13,543 | $ 13,111 | $ 12,577 | $ 12,419 | $ 12,462 | $ 12,535 | $ 12,635 | $ 12,793 | $ 12,980 | $ 13,152 | $ 128,206 |
| Maint | $ (1,000) | $ (1,009) | $ (1,018) | $ (1,027) | $ (1,036) | $ (1,046) | $ (1,055) | $ (1,065) | $ (1,074) | $ (1,084) | $ (10,415) |
| Operational Savings | $ 12,543 | $ 12,102 | $ 11,559 | $ 11,392 | $ 11,426 | $ 11,489 | $ 11,580 | $ 11,728 | $ 11,905 | $ 12,068 | $ 117,791 |
| Cash flow | $ (11,529) | $ 12,102 | $ 11,559 | $ 11,392 | $ 11,426 | $ 11,489 | $ 11,580 | $ 11,728 | $ 11,905 | $ 12,068 | $ 93,719 |
| | | | | | | | | | | | |
| Discounted energy savings | $ 13,344 | $ 12,542 | $ 11,681 | $ 11,198 | $ 10,910 | $ 10,654 | $ 10,426 | $ 10,249 | $ 10,096 | $ 9,932 | $ 111,033 |
| Discounted Maint | $ (985) | $ (965) | $ (946) | $ (926) | $ (907) | $ (889) | $ (871) | $ (853) | $ (836) | $ (819) | $ (8,997) |
| Discounted CF | $ (11,360) | $ 11,577 | $ 10,736 | $ 10,272 | $ 10,003 | $ 9,765 | $ 9,555 | $ 9,396 | $ 9,260 | $ 9,114 | |
| Total operational savings | | | | | | | | | | | **$ 102,037** |
| Payback | | | | | | | | | | | **1.92** |
| NPV | | | | | | | | | | | **$ 77,169** |
| IRR | | | | | | | | | | | **102.23%** |
| SIR | | | | | | | | | | | **4.24** |
| Disc. Rate | 3% | | | | | | | | | | |
| Inflation | 0.90% | | | | | | | | | | |

Table 29 – Base cash flow analysis, CO/O2 trim technology

| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | TOTAL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Investment | $ (36,865) | | | | | | | | | | $ (36,865) |
| Energy Price Variation | | -3.19% | -4.07% | -1.26% | 0.35% | 0.58% | 0.80% | 1.25% | 1.46% | 1.33% | |
| Savings | $ 17,063 | $ 16,519 | $ 15,846 | $ 15,647 | $ 15,701 | $ 15,792 | $ 15,919 | $ 16,118 | $ 16,353 | $ 16,571 | $ 161,528 |
| Maint | $ (1,500) | $ (1,514) | $ (1,527) | $ (1,541) | $ (1,555) | $ (1,569) | $ (1,583) | $ (1,597) | $ (1,611) | $ (1,626) | $ (15,622) |
| Operational Savings | $ 15,563 | $ 15,005 | $ 14,319 | $ 14,106 | $ 14,147 | $ 14,224 | $ 14,336 | $ 14,521 | $ 14,742 | $ 14,945 | $ 145,906 |
| Cash flow | $ (21,302) | $ 15,005 | $ 14,319 | $ 14,106 | $ 14,147 | $ 14,224 | $ 14,336 | $ 14,521 | $ 14,742 | $ 14,945 | $ 109,041 |
| | | | | | | | | | | | |
| Discounted energy savings | $ 16,813 | $ 15,802 | $ 14,717 | $ 14,109 | $ 13,746 | $ 13,423 | $ 13,136 | $ 12,913 | $ 12,720 | $ 12,514 | $ 139,892 |
| Discounted Maint | $ (1,478) | $ (1,448) | $ (1,418) | $ (1,389) | $ (1,361) | $ (1,333) | $ (1,306) | $ (1,280) | $ (1,253) | $ (1,228) | $ (13,495) |
| Discounted CF | $ (20,989) | $ 14,354 | $ 13,299 | $ 12,719 | $ 12,385 | $ 12,089 | $ 11,830 | $ 11,633 | $ 11,466 | $ 11,286 | |
| Total operational savings | | | | | | | | | | | **$ 126,397** |
| Payback | | | | | | | | | | | **2.37** |
| NPV | | | | | | | | | | | **$ 88,752** |
| Adjusted IRR | | | | | | | | | | | **16.51%** |
| SIR | | | | | | | | | | | **3.43** |
| Disc. Rate | 3% | | | | | | | | | | |
| Inflation | 0.90% | | | | | | | | | | |

The following economic parameters were calculated:

- Discounted total operational savings over the 10 year utilization period.
- Payback time, calculated relative to savings during the first year of operation.
- Net present value (NPV).
- Adjusted IRR as prescribed by the FEMP standard.
- Savings to investment ratio (SIR) as ratio between the operational savings and the first cost associated with the system installation.

Variations to changing assumptions were also calculated and are reported in the figures and tables below.

Table 30 – Economic indicators for changing utilization profile (25 MMBtu/h)

| | Payback (years) | | NPV | | Adjusted IRR | | SIR | |
|---|---|---|---|---|---|---|---|---|
| Profile | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim |
| 1 | 1.9 | 2.4 | $ 77,169 | $ 88,752 | 19.00% | 16.51% | 4.24 | 3.43 |
| 2 | 1.9 | 2.5 | $ 78,001 | $ 84,351 | 19.10% | 16.09% | 4.27 | 3.31 |
| 3 | 4.1 | 4.0 | $ 23,216 | $ 37,488 | 10.19% | 10.49% | 1.96 | 2.02 |
| 4 | 0.9 | 1.4 | $ 185,100 | $171,945 | 28.01% | 22.62% | 8.79 | 5.72 |
| 5 | 2.0 | 2.3 | $ 75,446 | $ 91,511 | 18.80% | 16.76% | 4.17 | 3.50 |

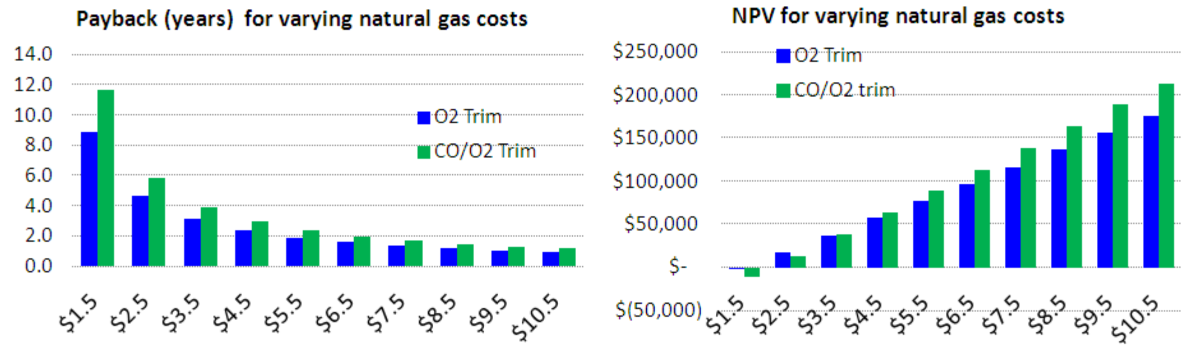



Figure 72 – Sensitivity to natural gas price variation of payback and NPV (25 MMBtu/h)

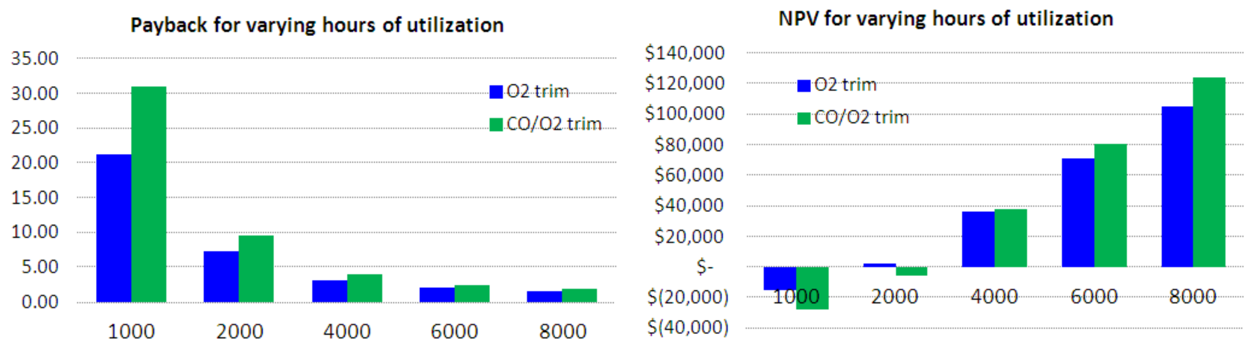



Figure 73 – Sensitivity to boiler utilization variation of payback and NPV (25 MMBtu/h)

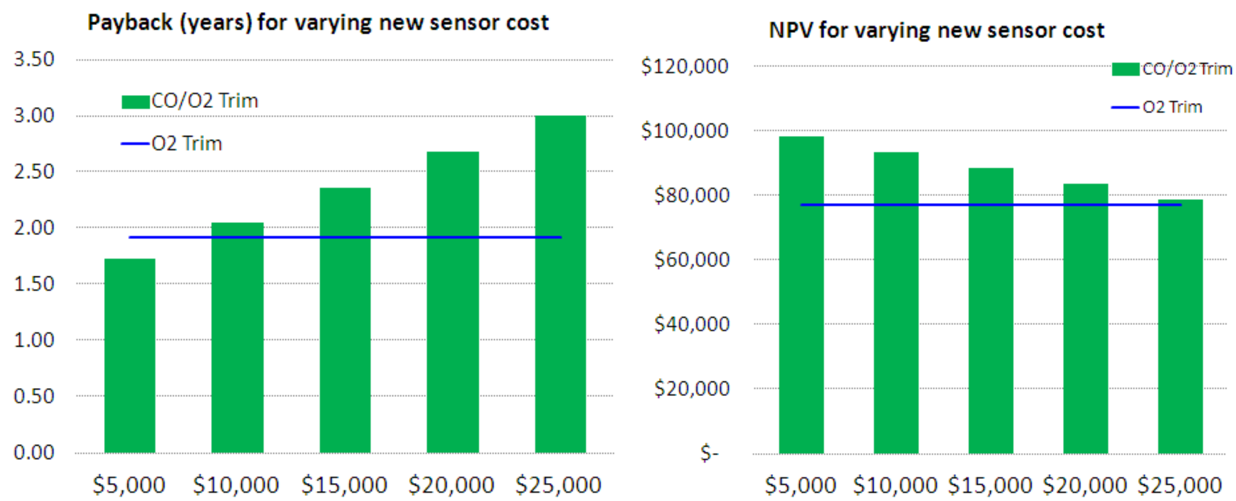



Figure 74 – Sensitivity to cost of CO/O2 probe of payback and NPV (25 MMBtu/h)

Table 31 – Economic indicators for changing utilization profile (100 MMBtu/h)

| | Payback (years) | | NPV | | Adjusted IRR | | SIR | |
|---|---|---|---|---|---|---|---|---|
| Profile | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim | O2 trim | CO/O2 trim |
| 1 | 0.5 | 0.6 | $ 400,528 | $497,416 | 35.01% | 33.16% | 14.97 | 13.04 |
| 2 | 0.5 | 0.6 | $ 403,856 | $479,812 | 35.11% | 32.72% | 15.08 | 12.62 |
| 3 | 1.1 | 1.0 | $ 184,715 | $292,360 | 25.88% | 26.92% | 7.43 | 8.07 |
| 4 | 0.3 | 0.4 | $ 832,251 | $830,189 | 44.75% | 39.73% | 30.04 | 21.11 |
| 5 | 0.6 | 0.6 | $ 393,637 | $508,455 | 34.79% | 33.43% | 14.73 | 13.31 |

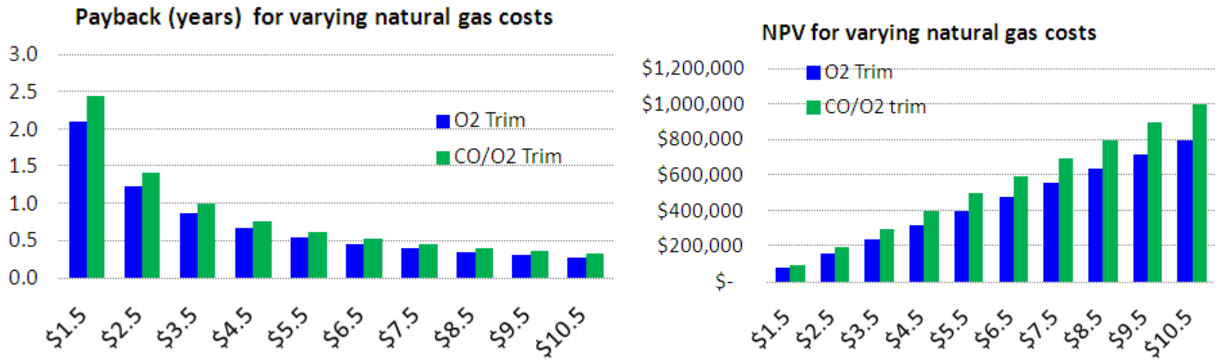



Figure 75 – Sensitivity to natural gas price variation of payback and NPV (100 MMBtu/h)

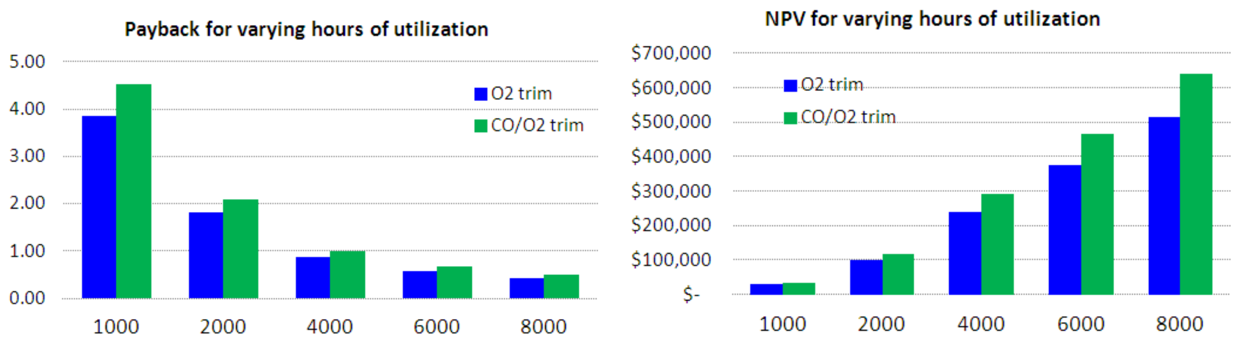



Figure 76 – Sensitivity to boiler utilization variation of payback and NPV (100 MMBtu/h)

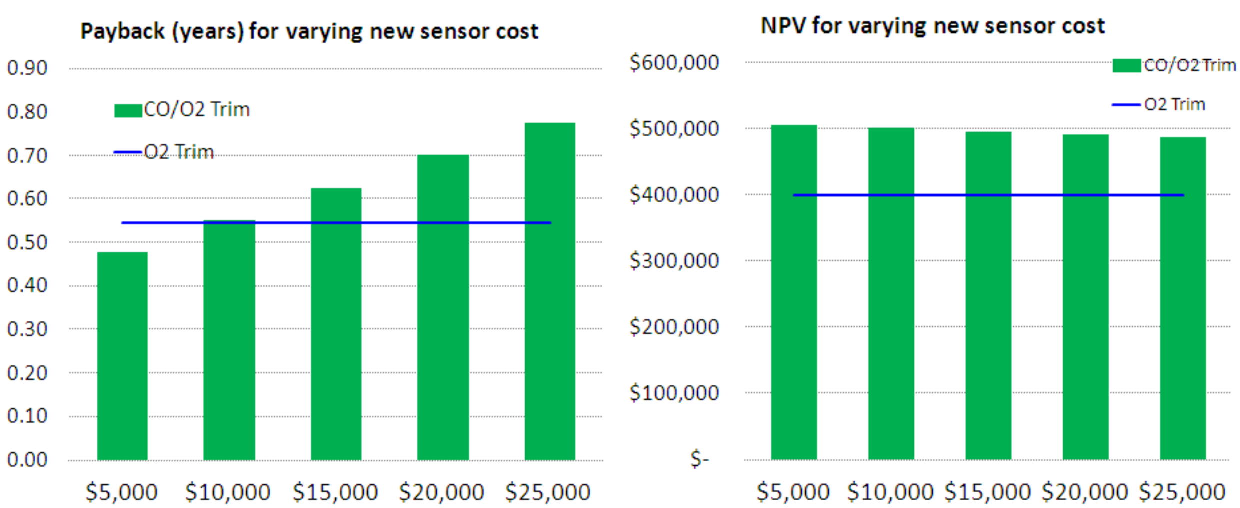



Figure 77 – Sensitivity to cost of CO/O2 probe of payback and NPV (100 MMBtu/h)

The same analysis was performed for a 25MMBtu/h boiler running on No. 2 oil, comparing baseline operation with O2 trim only. Economic performance of the investment is here extremely appealing, principally because of the higher efficiency gains and the current cost of oil.

Table 32 – Economic indicators for changing utilization profile (25 MMBtu/h, oil)

| Profile | Payback (years) O2 trim | Payback (years) CO/O2 trim | NPV O2 trim | NPV CO/O2 trim | Adjusted IRR O2 trim | Adjusted IRR CO/O2 trim | SIR O2 trim | SIR CO/O2 trim |
|---|---|---|---|---|---|---|---|---|
| 1 | 0.2 | | $ 1,121,826 | | 51.78% | | 48.28 | |
| 2 | 0.2 | | $ 1,146,289 | | 52.10% | | 49.31 | |
| 3 | 0.3 | | $ 583,717 | | 42.45% | | 25.60 | |
| 4 | 0.1 | | $ 2,260,058 | | 62.62% | | 96.27 | |
| 5 | 0.2 | | $ 1,146,030 | | 52.10% | | 49.30 | |

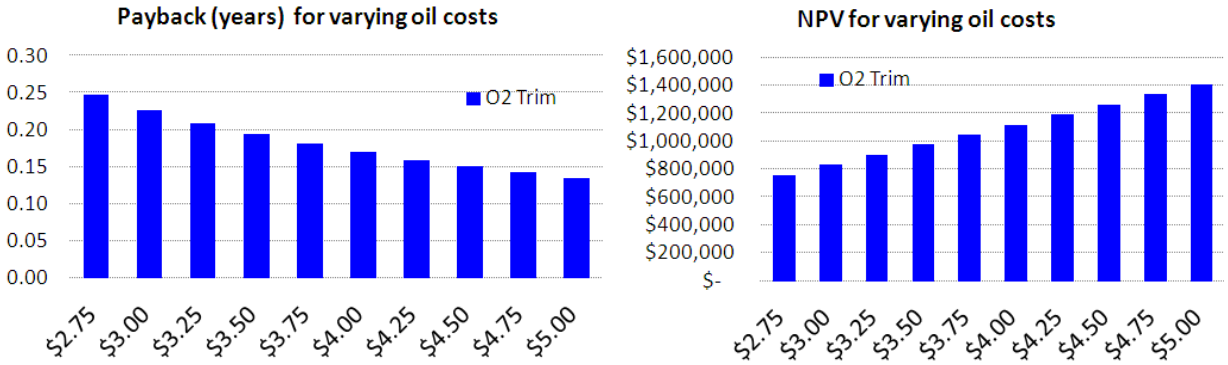



Figure 78 – Sensitivity to oil price variation of payback and NPV (25 MMBtu/h)

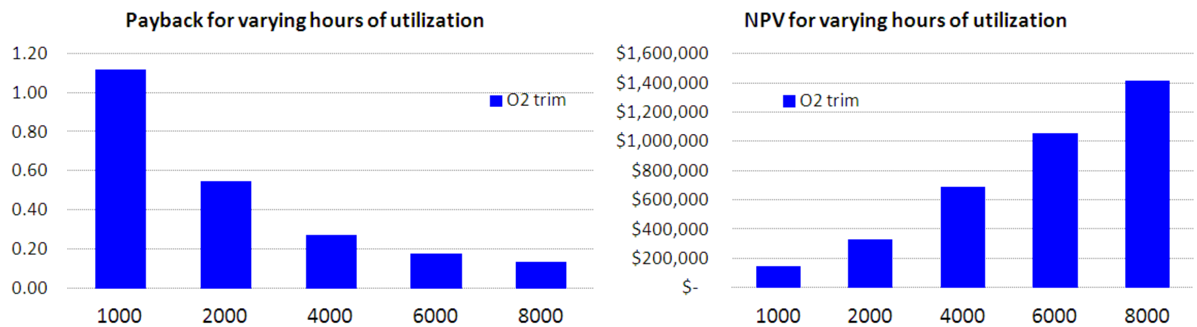



Figure 79 – Sensitivity to boiler utilization variation of payback and NPV (25 MMBtu/h, oil)

From the analysis reported above, the following can be concluded:

- For a typical boiler utilization profile, the application of new controls to natural gas fired boilers similar to that used for demonstration would enable fuel savings of about 3% for O2 trim technology and 4% for CO/O2 trim. Savings associated with No. 2 oil utilization would be 7% for O2 trim technology.
- Fuel savings variations are less than 1% when a different utilization profile is assumed.
- As one would expect, fuel cost savings scale linearly with boiler size as well as with cost of energy. Notwithstanding a downward trend of natural gas fuel costs, the adoption of new control technology enables significant savings. For No. 2 oil, predicted savings are much higher than with natural gas.
- An increase of boiler utilization leads to increased fuel savings. This trend is also expected. In summary, boiler size, utilization and cost of fuel are the most important drivers to achievable fuel cost savings and on the overall value of the investment.
- Attractive payback and NPV are achievable by adopting combustion control solutions. Payback time for natural gas is in the order of 2 years for a 25 MMBtu/h boiler, less than a

year for larger 100 MMBtu/h boilers). O2 trim technology has lower payback times than CO/O2 trim, but also lower NPV. Payback differences are in the order of months. Variation of sensor first cost has an impact on payback times, but less so than other factors such as the cost of fuel. For oil, payback time is in the order of months for O2 trim technology.

- The target of <1 year payback was not met, in part because the expected efficiency gains were not attainable on the Watervliet boiler, but also because the price of natural gas dropped sensibly relative to when objectives were set in 2010.

### 7.3.3 Overall Value of Investment to DoD

The Army owns 214 sites with >10 MMBtu/h oil/gas boilers for a total capacity of almost 34,000MMBtu/h, more than 90% of which are older than 10 years[4]. The total boiler capacity for DoD can be estimated at 82,000 MMBtu/h by scaling proportionally with total owned building area (data from [FRPC 2006] and [Andrews 2009]). By scaling to the total output estimate the results obtained for the 25 MMBtu/h with natural gas, one can estimate the overall annual energy cost savings attainable for DoD overall. Since about 20% of the Army boilers operate exclusively with oil, the analysis was performed based on natural gas data for 80% of capacity even if some of the boilers operate in dual fuel mode. Since a comparison between O2 trim and CO/O2 trim potential energy savings was not performed for oil, the same relative efficiency gain observed for natural gas (with profile #1) was applied to oil for CO/O2 trim operation.

Table 33 – Estimate of overall DoD annual savings and carbon reduction

| **DoD boiler inventory size** | | | | |
|---|---|---|---|---|
| DoD total area of building inventory | 2,112 MMsqft | | | |
| Army total area of building inventory | 870 MMsqft | | | |
| Army total oil/gas boiler capacity, plants > | 33,773 MMbtu/hr | | | |
| # of sites | 214 | | | |
| # of sites, installation >10years old | 196 | | | |
| DoD est installed capacity >10MMbtu cer | **81,991** MMbtu/hr | | | |
| Of which oil | **20%** | | | |
| | **GAS** | **OIL** | **TOTAL** | |
| Total DoD capacity | 65,593 | 16,398 | 81,991 | |
| Annual fuel consumption - baseline | 208,106,497 | 333,980,589 | 542,087,086 | MMbtu |
| Savings O2 trim | 6,460,472 | 23,426,150 | 29,886,622 | MMbtu |
| Savings CO/O2 trim | 8,139,606 | 26,120,917 | 34,260,523 | MMbtu |
| Energy cost savings - O2 trim | **$ 35,532,594** | **$ 93,704,601** | **$ 129,237,196** | |
| Energy cost savings - CO/O2 trim | **$ 44,767,835** | **$ 104,483,668** | **$ 149,251,503** | |
| Avoided CO2 emissions - O2 trim | **378,261** | **262,139** | **640,399** | ton |
| Avoided CO2 emissions - CO/O2 trim | **476,574** | **292,293** | **768,867** | ton |

The calculations above were performed for the base case with profile #1 and $5/MMBtu cost of natural gas and $4/gal for No. 2 oil. Under those assumptions, with the introduction of CO/O2 trim technology, DoD has a potential saving opportunity of $150M every year, as opposed to yearly $130M for O2 trim only. Annual reduction of more than 760 ton of $CO_2$ emissions can also be estimated.

[4] Information extracted from data on the Army boiler inventory as of July 2009 available from the Army Headquarters Installation Information System, courtesy of the Army Corps of Engineers.

# 8. IMPLEMENTATION ISSUES

This demonstration utilized the O2 trim Fireye PPC4000 Air/Fuel Ratio Control which is commercially available from Fireye, Derry, NH. The system consists of the PPC 4000 controller, servomotors, NXD410 User Interface and a NXCESO2-1001 oxygen probe. These components are readily available from local distributors who are trained and familiar with their installation. All of the hardware is UL certified. Full deployment was completed in 3 days, including commissioning. Upgrade from the linkage-based boiler control system required replacement of the existing butterfly valve assembly with a servomotor-driven valve assembly for both the fuel and air linkages. This process is straightforward, however some welding maybe required depending on the existing flange spacing on the fuel supply line. Although the air supply assembly will not employ flanges, precise alignment to the existing control arm is required. The PPC4000 controller can operate up to 10 servomotors so dual fuel control, for example natural gas and oil, as in this demonstration, is easily configurable.

To control the servomotors the PPC4000 was located in a NEMA enclosure near the boiler. The user interface to the controller was located in the control room approximately 30 ft away. A 4 line, 40 character display allows monitoring of system variables and easy parameter changes. Problems were not encountered during the installation at Watervliet Arsenal and a scenario where the controller could not be deployed due to physical constraints cannot be envisioned.

Notwithstanding that electronic boiler controls are becoming more known in the US, still a lot of work has to be done to diffuse the knowledge about their benefits (only an estimated 10% of boilers have electronic controls, versus 60% in Europe and worldwide based on information from Fireye). User concerns over deployment of a digitally controlled O2 trim system should be mitigated by this demonstration which illustrated efficiency gain, reduced emissions and reliable performance over a full heating season. Downtime during installation was at most 3 days and full installations have been performed by Fireye trained distributors at other sites in 1 day only. The PPC4000 is a proven product with a very low failure rate. The system can always revert to manual control if a problem is encountered. Through this demonstration, UTRC and Fireye did not find any reason to avoid upgrade of the burner management system to closed-loop control. Regulations that would prevent adoptions are currently not known. Emission levels observed during the demonstration were sufficiently low to always meet emission regulations.

Update to CO/O2 trim technology would require similarly a setup of a PPC4000 controller and servomechanisms. However, the oxygen measurement probe would be replaced by a multi-sensor box which included $O_2$ as well as CO concentration measurement. Tuning and commissioning of the system would require the set up of additional control parameters as illustrated in Section 5.4.5. Education and training for use of this new control feature would be necessary for adoption and to ensure that efficiency gains can be the highest possible.

## 8.1 ADAPTATION TO SITE

WVA is a well operated facility and incorporation of a new controller proved seamless. The GUI for the controller was readily installed in available space on the control panel in the control room. Changes to the boiler involved mounting of the servomotors and careful alignment with

the linkage rod for the air valve. Problems were not encountered during the installation and startup of the PPC4000. When applied to other sites, system installation activities would have to adapt to specific configurations, depending on the type of boiler, space available, requirements of boiler operator. The introduction of the CO/O2 trim technology would not create additional adaptation needs that those encountered for the PPC4000 today. Ease of configuration through the user interface panel and the ability to upload profiles via SD card would certainly simplify installation time.

## 8.2 ACCURATE TUNING

The commissioning process was straightforward and performed by Joe Firlet of Steam Plant Systems and Barry Neill of Fireye. A handheld gas analyzer is used in conjunction with temperature, pressure, fuel and steam flow readings to set a 12 point air to fuel ratio profile for operation of the boiler from low to high fire, for each fuel use. Different profiles can be set to adapt to different operation conditions. The O2 trim system will also have an O2 set point associated with each point in the profile and the controller will close the loop on this value.

Tuning of the CO/O2 trim controller requires particular attention and care during the commissioning phase, as it introduces new parameters and requires precision in setting the traditional O2 trim parameters. A list of recommendations was developed as part of the demonstration:

- The trim limits should be set so that the controller can reach air/fuel ratios allowing operation at low $O_2$ concentrations in proximity of the stoichiometric boundary. This can be verified during the commissioning phase by the installer.
- The O2 trim closed loop control parameters (proportional and integral gains, transport delay) need to be tuned so that measured $O_2$ concentration tracks the target with precision. On the other hand, settings should not be so “aggressive” to generate a response to micropulsing.
- Adjustment times for micropulsing and $O_2$ target reset should be long, in the order of tens of minutes, to allow the controller to adjust to new, higher efficiency, conditions. This was considered acceptable for boilers which operate for long hours.

## 8.3 APPLICABLE REGULATIONS

Boilers are regulated under the new EPA rule: “National Emission Standards for Hazardous Air Pollutants for Industrial/Commercial/Institutional Boilers and Process Heaters” which is currently being implemented. A “No action assurance” for boiler operators is currently in effect through October 2012. The boilers under consideration require compliance of the “Area Source Rule”, for “existing sources” larger than 10 MMBtu/h. For this category of boilers, emission limits under the rule do not apply, but a yearly tuneup of the boiler system has to be performed. The rule does not discuss expressly the use of using digital controls. The use of electronic controls in lieu of mechanical one would provide immediate measurement of emissions and greatly simplify recommissioning procedures.

Boiler control technology adoption in all DoD facilities is regulated under the Unified Facility Criteria with criterion UFC 3-430-11 “BOILER CONTROL SYSTEMS” issued on 14 February 2001. Operation along the lines of the CO/O2 trim control algorithm is discussed in section 5.2-

13.3.1 with great level of detail as follows: “Carbon monoxide (CO) analyzers used in a boiler plant may utilize a catalytic element, wet electrochemical cell, or non-dispersive infrared absorption. Install the CO analyzer in a clean gas stream that is downstream of the particulate removal system. A CO analyzer permits firing at lower oxygen levels than without it. A minimum air requirement is established by decreasing oxygen in the stack gas until a large increase in the CO reading occurs. A CO analyzer is also useful in boiler startup. During start-up monitor the CO analyzer closely for unsafe firing conditions. High CO readings indicate incomplete combustion, which implies potentially unsafe conditions in the furnace.” Further, application guidelines for maintenance and upkeep of CO/O2 trim technology could be included in UFC 3-430-07 “OPERATIONS AND MAINTENANCE: INSPECTION AND CERTIFICATION OF BOILERS AND UNFIRED PRESSURE VESSELS”, particularly relative to changes with inspection requirements that the new technology would require. Finally, the creation of technical notes such as those issued by the U.S. Army Corps of Engineers [USACE] could be used as a vehicle to facilitate adoption and inform boiler operators and installation energy managers of the availability of a new, state of the art technology.

While electronic boiler control has been available for more than two decades, and is used broadly in Europe and the rest of the world, adoption in the US (and DoD) has been slow, so much that only an estimated 10-20% of the boilers use digital efficiency controls. Emphasizing and following the guidelines indicated in the UFC when boiler plant overhaul or maintenance occur would be a first good practice to ensure broader adoption. DoD would have the opportunity to lead the boiler user base, serving as an example. Championing at the Facility Command level for the three main DoD services would help to diffuse knowledge to all installations of electronic controls and potentially the use for control purposes of CO monitoring. For example, NAVFAC has created the Navy Technology Demonstration and Validation (TECHVAL) with the purpose of demonstrating new technology to augment and diffuse knowledge. TECHVAL could be used to demonstrate advanced boiler control. Venues such as the GovEnergy conference should be used to increase awareness and educate boiler operators.

## 8.4 PATH TO IMPLEMENTATION AS PRODUCT & ADOPTION

The CO/O2 trim technology was demonstrated at TRL6 as a prototype operating on a real environment. Additional operational savings to those achievable with O2 trim only were demonstrated, with a potential of additional 1% savings on boilers similar to that used for demonstration. It was considered that results obtained in demonstration should be a lower attainable limit, given that the boiler and burner are well maintained and were already operated quite efficiently. At current natural gas fuel prices, payback of about 2-2½ years is possible at an attractive net present value. When operated with oil fuel, O2 trim technology enabled 7% savings. The use of CO/O2 technology could not be tested with oil.

To achieve TRL8 (fully qualified, approved, commercially released product) with the CO/O2 trim system, the following steps will need to be pursued by Fireye:

- System and software optimization will be required to make the system to conform to a commercially viable product release and obtain safety certification by UL and FM Global;
- Additional testing of the prototype will be required, especially on several additional boilers to ensure adaptation to multiple sites. The dual CO sensor system implemented at WVA worked

flawlessly during a 2 month test period. However, the sensor system is still considered a prototype and is not UL certified.
- Certification by UL and FM Global.

UTC companies have a proven process for product engineering and commercialization, the Passport process that will be used for commercialization of the proposed technology.

The technology demonstrated with this project will be suitable for acquisition and adoption by installations which manage and operate directly their boilers by means of the Energy Conservation Investment Program (ECIP). Where operation of equipment is managed via Energy Service Companies (ESCOs) or Utility Energy Service Contracts (UESC), adoption will have to occur as part of a portfolio of energy improvements selected by the private companies. The installation will pay a rate for generation of hot water or steam. In this case, the value of the investment in new technology will be captured by the service company who will transfer part of the benefit to the installation in terms of a rate discount.

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# APPENDICES

## APPENDIX A: POINTS OF CONTACT

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